A COMPARISON OF WINAM AND ENERGYPLUS PREDICTED CONSUMPTION DUE TO THE EFFECTS OF THERMAL MASS AND TEMPERATURE SETBACK

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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December 2018

Major Subject: Mechanical Engineering

ABSTRACT

The purpose of this research was to compare the energy consumption of WinAM and EnergyPlus when thermal mass and a temperature setback are applied. Since WinAM does not account for thermal mass, a correction method was developed to correct the predicted savings produced by a temperature setback. This correction method accounts for thermal mass, wall resistance, building size, and wall area, and works best for climates with a wide range of temperatures.

Hourly cooling coil and heating coil energy were plotted versus outside temperature for WinAM and EnergyPlus with varying wall constructions, climates, and temperature schedules, totaling 18 EnergyPlus simulations and 6 WinAM simulations. Consumption from these results were summed to calculate the monthly cooling and coil energy. For each simulation, the difference between energy consumption for a temperature setback and no setback were calculated for each month; this value is the predicted savings produced each monthly by implementing a temperature setback. The difference in predicted savings between WinAM and EnergyPlus was then plotted versus outdoor air temperature. This was used to create the correction method that adjusts WinAM predicted savings to better match EnergyPlus predicted savings.

Results indicate WinAM under predicting hourly cooling and heating coil energy. Results also show WinAM over-estimating the predicted savings due to temperature setback by 200-1000 Btu/ft^2 depending on the temperature. By implementing the WinAM correction method, the WinAM over-estimation is reduced to 30-150 Btu/ft^2. The calculated percent reduction in the difference between EnergyPlus and WinAM predicted savings is up to 99%.

The large reduction in the difference between WinAM and EnergyPlus predicted savings indicates the correction method works well for the simulations produced. Implementing the correction method leads to a WinAM model that more accurately predicts temperatures setback savings when thermal mass is applied.

ACKNOWLEDGEMENTS

I first and foremost want to thank my adviser, Dr. Claridge, for all his help and calming demeanor through the research process. I would also like to thank my committee for their helpful revisions, Michael Witte for guiding me through EnergyPlus, and my family and friends for their support. Finally, I want to give a sincerest thank you to all my professors, both at Texas A&M University and Oklahoma State University, for educating me and providing me with the knowledge necessary to complete this thesis.

CONTRIBUTORS AND FUNDING SOURCES

This work was supported by a dissertation committee consisting of Dr. Claridge and Dr. Pate of the Department of Mechanical Engineering, and Dr. Culp of the Department of Architecture.

Graduate study was supported by a Graduate Teaching Assistantship from Texas A&M University.

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INTRODUCTION

I.I Background

Buildings in America make up roughly 40% of all energy consumption (U.S. Energy Information Administration, 2017). Because of this, interest in minimizing building energy has increased through recent years. Energy modeling is a powerful tool that can predict building consumption and can be used to optimize building performance. Many different modeling tools are being used in the field, some more complex than others. All programs require user inputs related to building geometry, weather, and mechanical systems; where the programs diverge is in the complexity of these inputs and the computations that follow. The Energy Systems Laboratory at Texas A&M University has developed a building energy simulation tool called WinAM, short for Windows Air Model. WinAM is used to predict savings and provide energy efficiency measures in a process called Continuous Commissioning®. Unlike the more complex modeling programs, WinAM does not account for solar gains or the thermal mass of a building. WinAM calculates energy use one hour at a time, each independent of the hour before. This simplified approach allows for faster computation and fewer user inputs. However, this also leads to inaccuracies for buildings that have higher thermal mass or solar loads. Thermal mass effects lead to difficulties in determining heat up or cool down times in a building utilizing setback temperatures; a building with no thermal mass quickly adjusts to temperature changes, but a building with high thermal mass requires more time. A building needs enough time to heat up or cool down to a defined temperature before it becomes occupied again to maintain comfort. Since

WinAM does not account for thermal mass, there will be inaccuracies in load predictions; these inaccuracies will be exacerbated when setbacks are implemented in the model.

I.II Objective

The overall objective of this research is to maximize the accuracy and potential of WinAM energy simulation while maintaining its user-friendly interface and quick computation time. This goal is accomplished by comparing the energy output data of WinAM with a more detailed simulation tool – specifically EnergyPlus. Both the strengths and shortcomings of WinAM can be determined by analyzing key outputs compared to EnergyPlus. These outputs include, but are not limited to, heating coil energy, cooling coil energy, fan electric usage, and overall electric usage. This project will focus mainly on heating and cooling coil energy usage effects related to thermal mass and temperature setbacks. From this investigation, a simple mathematical method will be developed to approximate thermal mass effects in WinAM without heavy computation or transient analysis.

CHAPTER II

LITERATURE REVIEW

II.I Energy Modeling Tools

Over the years there has been extensive research into the robustness of varying building energy modeling tools. Some of these tools include EnergyPlus, eQUEST, simple RC models, and DOE 2.1E. Due to the frequent use of energy modeling in industry, simplifying the modeling process has garnered attention (Tiwari, 2016). In his thesis, Tiwari's goal is to validate the results of a moderately complex modeling tool, eQUEST, with metered data to determine if simplified models accurately predict energy consumption. Tiwari also identifies key performance indices (KPI) to be altered to determine their effects on a simplified model. The KPI's include lighting, occupancy, climate, and schedules. These KPI's are important because eQUEST requires fewer inputs than other complex modeling tools, such as EnergyPlus; the fewer inputs needed, the larger their effects will be on the energy model output. Tiwari completed parametric runs changing his baseline model one KPI at a time to establish the sensitivity of each. He found that occupancy and schedules have the highest sensitivity in the model; an 8% incremental electricity consumption increase occurred per 50 ft^2/person increase of occupancy, and a 22% linear increase in electricity consumption occurred for each additional day per week of building operation each year. Weather and lighting density both had a 3% consumption change for various inputs. Tiwari's research highlights the increased sensitivity of input parameters for simplified modeling tools over their more complex counterparts.

A comparison of EnergyPlus and eQUEST outputs for a medium sized office building was completed by Hema Sree Rallapalli (2010). This was done to identify the degree of closeness simulation tools have with actual metered data. The study ensures the models ran over the same period with similar settings and configurations for the best comparison. The two models were then evaluated on usability, functionality, reliability, and prevalence. The level of reliability of the eQUEST and EnergyPlus models is determined by comparing electric consumption, space cooling, and gas consumption of each model with metered data. For yearly electricity consumptions, eQUEST was within 1.65% of the metered data and EnergyPlus was within 0.91%. For yearly gas consumptions, eQUEST was within 0.5% of the metered data and EnergyPlus was within 65.8%. From these results, Rallapalli claims eQUEST has greater reliability due to the large inaccuracy of EnergyPlus gas consumption prediction. Usability is determined by comparing the user interface of the programs; Rallapalli states eQUEST has a better visual interface than EnergyPlus, making it more favorable to the user. Functionality is determined by comparing the simulation time; Rallapalli recommends eQUEST's 30 second run time over EnergyPlus's 35-minute run time.

Another study conducted by Bryan Urban and Leon Glicksman (2007) investigates simplified energy modeling for nontechnical users. Its purpose is to simplify energy modeling while maintaining accuracy, similar to the purpose of WinAM. Urban and Glicksman want to combat overly complicated simulation tools by creating an easy to use interface and focusing on early stage design. The paper discusses the draw backs of DOE2 and EnergyPlus, including their complicated inputs, lack of user interface, and complex raw data outputs. The authors believe it is possible to have accurate results on a long-time scale without this complexity since full scale simulations are unrealistic in the early design stage. Urban and Glicksman compare their simplified model, The MIT Design Advisor, with an EnergyPlus model using the method listed below,

- Inputs entered on graphical setup with pre-selected defaults
- Uses TMY2 weather data
- Daylight module used once per hour to compute lighting intensity
- Heating and cooling loads of each zone computed using energy exchanges
    - Internal loads, envelope loads, ventilation/infiltration, thermal mass
- Results normalized by floor area and returned graphically
- All room loads, Qi, computed independently and only made as frequently as needed
- Qint constant for a given hour but change with schedule
- Heat transfer coefficients computed dynamically based on environmental conditions
- Radiation coefficients computed using linearized radiation heat transfer coefficient
- Transmitted fraction of incident rad computed each hour
- Radiant interactions between blinds, windows, walls are computed using radiosity method

They then use their proposed method to compare the energy consumption of eight different cases listed below,

- Adiabatic walls and ceiling, no windows, no internal load, no ventilation as baseline
    - Case 1: base + internal load with schedule
    - Case 2: case1 + ventilation
    - Case 3: case1 + insulation to east wall
    - Case 4: case 3 + ventilation

- Case 5: case 3 + added east facing window
- Case 6: case 5 + ventilation
- Case 7: case 5 + internal loads

This approach builds up a simple model to see effects of each individual input. The authors' thermal mass validation shows the agreement between MIT Design Advisor and EnergyPlus is within 2.1% for the cases considered. Their window solver validation shows agreement within 1%. From these results, Urban and Glicksman conclude that their simplified tool, The MIT Design Advisor, is comparable with more complex, industry standard simulation tools for estimating monthly or annual energy consumption.

Crawley, et al. (2005) efficiently compare features and capabilities of 20 major building energy simulation programs used in industry and research. The categories compared are listed below,

- General modeling features
- Zone loads
- Building envelope
- Daylighting and solar
- Infiltration, ventilation, and multizone airflow
- Renewable energy systems
- Electrical systems and equipment
- HVAC systems
- HVAC equipment
- Environmental emissions

- Economic evaluation
- Climate data availability
- Results reporting
- Validation
- User interface

The authors then go on to describe these features for the following programs: BLAST, BSim, DeSt, DOE-2.1E, ECOTECT, Ener-Win, Energy Express, Energy-10, EnergyPlus, eQUEST, ESP-r, IDA ICE, IES <VE>, HAP, HEED, PowerDomus, Sunrel, Tas, TRACE, and TRNSYS. The report includes a link to each simulation tool website for more information. The purpose of this report is to quickly detail the main features of each of the major programs so that researchers or those in industry can determine the best tool for their specific project. For example, displacement ventilation is only modeled in EnergyPlus, ESP-r, IDA ICE, IES <VE>, and Tas. For someone working on a project that includes displacement ventilation, one of these programs should be used over the others not listed. This report covers several other parameters for users to explore and determine the program best fit for their project.

The simplified energy analysis procedure, SEAP, developed by ASHRAE is used in industry as a way to estimate heating and cooling requirements in buildings (Balasubramanya, et. al, 1992). However, like WinAM, SEAP does not consider thermal mass, leading to discrepancies between the hourly energy predictions of SEAP and DOE-2. The authors mention that investigation shows the simplified solar gain calculation and lack of thermal mass to be the main contributors to such discrepancies. The purpose of this research is to compare the energy consumption prediction of SEAP with improved solar gain calculation and thermal mass treatment with that of DOE-2 and the original SEAP. Various parameters are varied, such as surface weight ratio, internal heat gain, room air throttling range, thermostat setback, and more. The authors found that the modified SEAP improved over the original SEAP in 80% of the 71 cases examined. All other cases showed similar or slightly worse predictions compared to DOE-2.

II.II Studies of Thermal Mass and Temperature Setbacks

Thermal mass and temperature setbacks are often used as a building control strategy (Braun, 2003). When the building is unoccupied, the thermostat can be set to a higher temperature for cooling or a lower temperature for heating. This allows for energy savings but also leads to comfort and control issues. Thermal mass plays a large role in the control issues of temperature setbacks. Buildings with high thermal mass store energy and take longer to adjust to a change in temperature setpoint. Because of this, Braun studies the optimization of zone temperature setpoints and system operating times. Through simulation, laboratory testing, and field demonstrations, Braun found that significant savings can be achieved through various setpoint strategies, such as precool, maximum discharge and slow linear rise. Precool is a strategy that lowers the setpoint temperature when a building is unoccupied and then maintains a fixed setpoint during occupied hours. Maximum discharge is similar to precool except the occupied setpoint temperature is increased. Slow linear rise is a modified version of maximum discharge, where the occupied setpoint is raised linearly over the occupied hours. Braun found between 17.1-22.7% annual savings for various precool strategies, 41.4% savings for maximum discharge, and 22% savings for slow linear rise.

From previous studies, it is known that thermal mass can impact the cooling and heating consumption of a building. However, many of these studies have been flawed because they failed to consider the interaction between occupancy and thermal mass (Reilly and Kinnane, 2017). Reilly and Kinnane also address the issue of high thermal mass in cold climates and its draw backs. Their research shows that high thermal mass in buildings that require more heating can lead to higher energy consumption. In their static model using Belfast weather data, the energy consumption is 15.4 MJ/m^2. The dynamic model that incorporates thermal mass has an energy consumption of 40.9 MJ/m^2. The static model was represented by an ideal massless wall. The dynamic model includes thermal mass with a thermal resistance equal to that of the static model. Reilly and Kinnane state that this increase in energy is due to the extra heat needed to warm up the high thermal mass walls each morning after a cold night. However, due to lack of research in thermal mass, the authors believe more research is needed before this assumption should be universally accepted.

Building energy management systems (BEMS) are being used to control buildings. BEMS use control techniques including on-off control, P control, PI control, PID control and start-stop routines. However, buildings have multi-variable behavior and thermal interactions that cannot be perfectly controlled. This leads to wasted energy and overshooting setpoints in the interest of being conservative (Perera and Skeie, 2016). However, Perera and Skeie note that several types of buildings, such as offices and schools, have regular occupancy hours that allow for simple temperature setback schedules. For example, an office building in the summer at night can raise the setpoint temperature up 5 to 10^{o}F and reduce the cooling load while maintaining vital indoor conditions. The authors' goal is to determine optimal setback temperatures and scheduling. A test building and a mathematical model were created to determine heat up/cool down times for four case studies. The heat up/cool down times are essential in defining the time to reset temperatures to maintain comfort for occupants return. Perera and Skeie also test two scenarios based on energy consumption rates. The rates are most expensive from 05:30-09:00 and 14:30-20:00. The first scenario has a 15°C setpoint from 01:00-03:00 then ramping up to 18°C. The second scenario ramps up to 18°C starting at 01:00 and then is steady starting at 05:30. Scenario 1 uses 2.79 kWh of energy and scenario 2 uses 3.03 kWh of energy. Although scenario 1 uses less energy, because of the timing of the rates and temperature setpoints, the costs of the two scenarios are almost identical. Because of this, Perera and Skeie conclude that the concept of low-cost heating is a faulty strategy.

High thermal mass envelope technologies are beginning to gain acceptance in the U.S. due to their ability to reduce building heating and cooling loads. (Kosny, et al., 2001). This reduction in energy consumption is largely due to the reduction of temperature swings and delaying thermal waves. Kosny and the other authors delve further into estimating the potential energy benefits of thermal mass. The authors use DOE2.1E to simulate the heating and cooling consumption of single-family residences in the U.S. with varying levels of thermal mass; twelve different wall constructions are simulated in ten different climates, totaling 120 simulations. They found that replacing a traditional lightweight wall with massive walls of the same R-value resulted in 8% annual savings in Minneapolis, a cold climate, and 18% annual savings in Bakersfield, a warm climate.

Existing structural mass of commercial buildings can be used to reduce energy and cost through the adjustment of temperature setpoints (Xu and Zagreus, 2009). This is done by pre-cooling a building at night then raising the setpoint to a more comfortable temperature during occupied hours. The thermal mass of a system can hold the cooled energy from the pre-cool, reducing the cooling needed during occupied hours. Heating setpoints should not be adjusted to avoid additional heating. Xu and Zagreus conducted tests in a heavy mass building and a light mass building. By implementing proper temperature setbacks and pre-cooling, the authors found reduction in the cooling load for both building types. The light mass building cooling load is reduced by roughly 35% on cool days and 25% on warm days. The heavy mass building cooling load is reduced by 30% year-round. Xu and Zagreus also found night pre-cooling reduces HVAC peak demand on the day following the pre-cooling.

School buildings are unoccupied up to three-quarters of a year, leading to excessive heating and cooling during those times (Guo and Nutter 2010). Recent field studies revealed that over a million square feet of school buildings disable night set back mode. In their study, Guo and Nutter use EnergyPlus to model two building envelopes with three orientations, three window areas, and 15 climate zones, totaling 540 building configurations. Standard cooling and heating setpoints of 23.9^{o}C and 21.1^{o}C are used, respectively. The authors also include a temperature setback for holidays, weekends, and evenings. Guo and Nutter tabulate annual gas and electric consumption savings from implementing a setback for their various models. Their results show annual gas consumption savings in the range of 8-64% depending on the setback temperature and climate zone. Results show annual cooling electricity consumption savings in the range of 17-77%. Guo and Nutter conclude that increasing the night setback does not guarantee energy savings because the optimal setback temperatures depend on the building structure and climate.

In their research, Szydlowski, Wrench, O'Neill, and Paton hope to disprove the thought that the energy saved by lowering the temperature setpoint at night during the heating season is lost when the building is brought back to a comfortable temperature during the day (Szydlowski, et al., 1993). The authors select six similar wooden administrative buildings to analyze. In setback mode, the buildings are maintained at 70^{o}F during occupied hours and 55^{o}F while unoccupied. The authors then compare the metered heating consumption of the six buildings in setback mode and single setting mode. They found that the night setback yields annual heating consumption savings of 14-25%, a mean of 19.2%, for the six buildings.

The literature reviewed each show links between temperature setback and thermal mass for varying climates. The research discussed reveal the importance of modeling thermal mass considering its impact on energy consumption. However, current literature does not account for the particular modeling tool, WinAM, that is being investigated in this thesis.

CHAPTER III

INPUT VALIDATION

The original intent of this research was to compare WinAM building energy modeling with EnergyPlus and metered data of a building on the Texas A&M campus. WinAM was created to predict the savings from applying various energy efficiency measures to buildings using simplified calculations with an easy to use interface that allows for a "good enough" model (WinAM 5.2, 2018). EnergyPlus is a whole building energy simulation program used to model energy consumption. EnergyPlus uses integrated, simultaneous solutions, heat balance-based solutions, sub-hourly time steps, combined heat and mass transfer model, and other more complicated algorithms to accurately model energy consumption. EnergyPlus can be used with OpenStudio to create a building structure which can then be customized further in an IDF editor or text editor (EnergyPlus, 2018). By comparing WinAM to a more robust simulation tool, we can easily tell where WinAM lacks accuracy and what can be done to further improve it as a modeling tool. The original goal of this research was to simulate several different types of buildings that would exacerbate the simplifications made in WinAM, such as the lack of thermal mass and solar load modeling. The different types of buildings that were going to be chosen were real buildings on the Texas A&M campus that would play to WinAM's weakness in order to determine the largest short-comings. Three different building types were decided upon: a highly glazed building since WinAM does not account for solar loads or orientation, a building with high thermal mass since WinAM does not account for setbacks and heat retention due to thermal mass, and a simple building to be used as a baseline comparison. Other parameters, such as pressurization, zoning, and infiltration were considered, but were deemed less important than solar loads and thermal mass effects. Before the process of modeling real buildings was conducted, it was decided that a simple box model would be developed to better understand the workings of EnergyPlus and WinAM. This was done so a simple hand calculation could be compared to the outputs of the simulations models to ensure they were running properly. As this process began, it quickly became evident that EnergyPlus is difficult to use and is full of minutiae that do not allow for quick and easy modeling. Because of this, much time was spent trying to match the simple box hand calculations with the EnergyPlus model. This ultimately led the research in a different direction due to complications and lack of time. The new direction of the research still focused on the effects of thermal mass on a building and the comparison of outputs between EnergyPlus and WinAM. However, a simplified building was used instead of a real campus building.

A simple box was created as an extremely simple building that could be used to ensure full understanding of EnergyPlus and WinAM. The simple box is a square building, one floor, 144,000 ft^2 (380 ft x 380 ft) with 12 ft walls. It has one zone with a setpoint temperature of 75^oF with no internal loads, windows, thermal mass, or outdoor air. The minimum flow rate is set at 1% of the design flowrate which was 1 CFM/ft^2. These parameters are tabulated in Table 1. These design constraints are used to simplify the hand calculation and negate the transient effects of solar gains, thermal mass, and people. The only loads felt by the simple box are conduction due to outside air temperature. With a simplified hand calculation, it is much easier to validate the inputs of EnergyPlus and WinAM. Weather data from College Station is used for the hand calculation, WinAM, and EnergyPlus, but EnergyPlus uses TMY2 weather data whereas the hand calculation and WinAM use separate hourly measured weather data provided by the Energy

Systems Lab. A VAV system was modeled for the entirety of the project because it is commonly used in large buildings, similar to the simplified box being simulated.

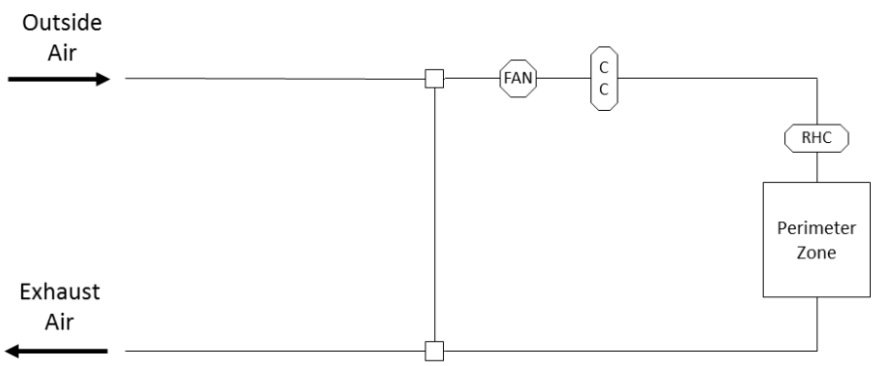

Figure 1: Simplified depiction of a VAV system taken from WinAM (WinAM 5.2, 2018)

Figure 1 shows a basic illustration of a VAV system. Outside air enters the system and is mixed with return air before entering the fan. The mixed are then passes over the cooling coil and is cooled to 55°F. Next, the air is reheated to a supply temperature determined by the amount of flow and zone temperature setpoint. Finally, the return air leaves the zone and is partially exhausted as the system repeats the cycle.

The following equations are used in the hand calculation to determine the heating and cooling required by the system.

$Q = UA(T_{OA} - T_z)\ [Btu/hr]$ **Equation 1**

The conduction, Q, through the walls and roof for every hour is calculated using Equation 1, where U is the thermal conductivity and has units of Btu/hr-ft^2-^{o}F, T_{OA} is the outdoor air temperature in ^{o}F and T_z is the zone set point temperature in ^{o}F.

$V = \frac{Q}{1.08(Tz - T_{CL})}$ $[CFM]$ **Equation 2**

The required flow rate, V, was calculated using Equation 2, where 1.08 is a constant value equal to the air density multiplied by the specific heat of air, and T_{CL} and the leaving temperature of the coil set at 55^{o}F. As mentioned above, the minimum flow rate was set to 1% of the design flow rate. The design flowrate is 1 CFM/ft^2, or 144,400 CFM. This means the minimum flowrate is set to 1444 CFM. If the calculated flowrate goes below the minimum, then the hand calculation resets the flowrate to be 1444 CFM. This occurs when the outdoor air temperature is less than the zone set point and the system goes into heating mode.

$T_S = T_Z - \frac{Q}{1.08V}$ $[^oF]$ **Equation 3**

The supply temperature, T_s, is calculated using Equation 3.

$q_{CL} = \frac{1.08V(T_Z - T_{CL})}{1{,}000{,}000}$ $[MMBtu]$ **Equation 4**

$q_{RH} = \frac{1.08V(T_S - T_{CL})}{1{,}000{,}000}$ $[MMBtu]$ **Equation 5**

The cooling required, q_{cl}, and heating required, q_{rh}, are calculated using Equation 4 and Equation 5, respectively.

III.I WinAM Input Validation

This section covers the validation of WinAM heating and cooling outputs with the hand calculation. This was done to ensure WinAM is behaving as expected.

Table 1: Baseline simple box input parameters

Run Number	1
Floor Area [ft^2]	144,400
Wall Area [ft^2]	30,400
Window Area [%]	0
T_{CL} [^{o}F]	55
Number of zones	1
Exposed to Solar	no
Exposed to Wind	no
Thermal mass	no
Wall/Roof Resistance [hr-ft^2-^{o}F/Btu]	40
Outdoor Air Flowrate [CFM]	0
Design Flowrate [CFM/ft^2]	1
Minimum Flowrate [%]	1
Lighting Load [W/ft^2]	0
People Load [people/ft^2]	0
Unoccupied Heating Setpoint [^{o}F]	75
Occupied Heating Setpoint [^{o}F]	75
Occupied Cooling Setpoint [^{o}F]	75
Unoccupied Cooling Setpoint [^{o}F]	75

Table 1 tabulates the most important parameters of the simple box used in the validation process. The cooling of the hand calculation and WinAM output were then plotted together to compare the results. It should also be noted that an adiabatic floor was used for all EnergyPlus models discussed in this paper. For the first set of calculations, a wall and roof resistance of 40 hr-ft^2-^{o}F/Btu was used.

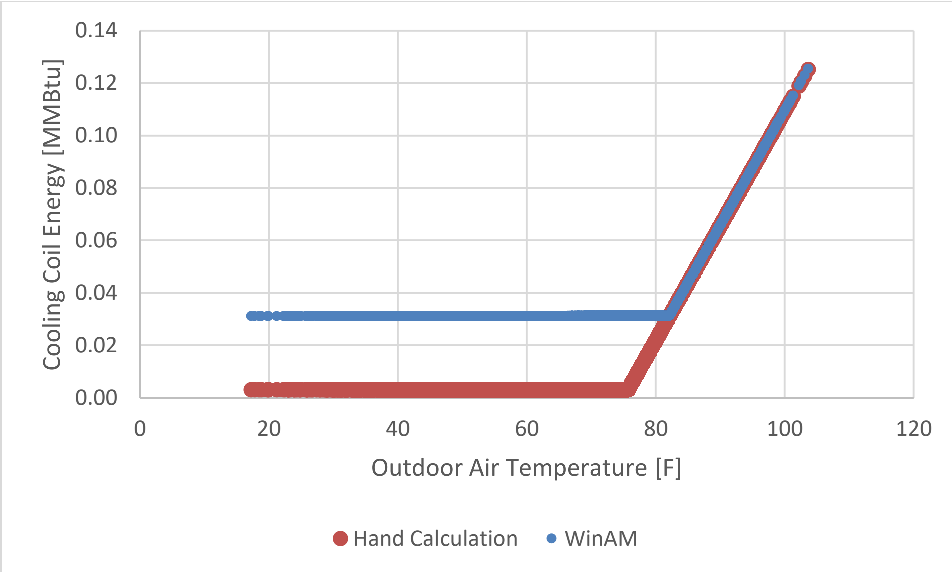

Figure 2: Cooling required for simple box using WinAM and hand calculation for simple box with an area of 144,400 ft^2 and wall resistance of 40 hr-ft^2-^{o}F/Btu

Figure 2 represents the cooling required for the simple box for WinAM and the hand calculation. The figure shows a discrepancy between the hand calculation and WinAM for temperatures below 76^{o}F for the model with a floor area of 144,440 ft^2 and a resistance of 40 hr-ft^2-^{o}F/Btu. The ratio of the WinAM cooling coil energy to the hand calculation is 10 to 1 at temperatures below 76^{o}F; WinAM outputs a cooling load of 0.031 MMBtu while the hand calculation outputs a load of 0.0031 MMBtu This means WinAM is predicting ten times as much cooling required to the space in temperatures below 76^{o}F than the hand calculation predicts. The same calculations are repeated with various wall resistance and floor area values to help determine WinAM's behaviors. All other parameters listed in Table 1 remained the same for the following simulations.

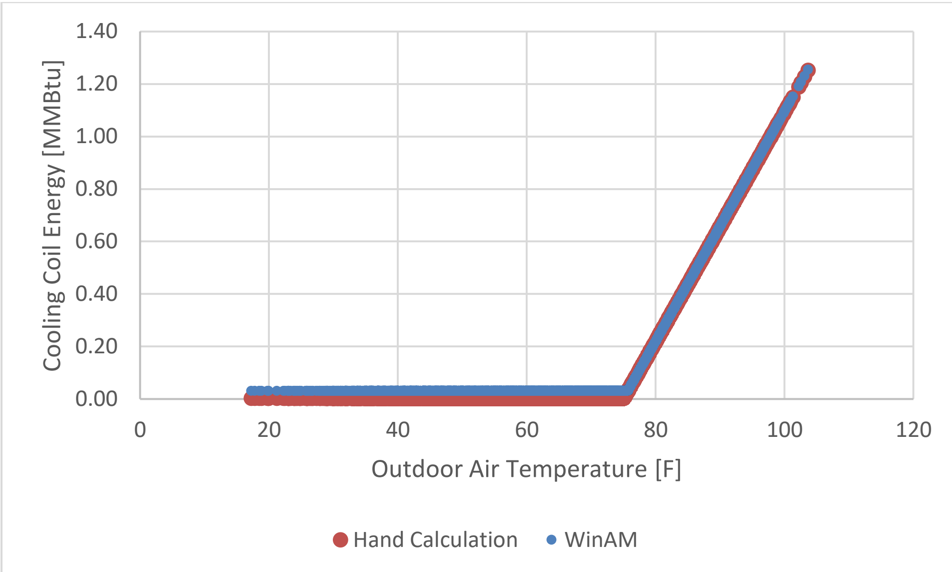

Figure 3: Cooling required for simple box using WinAM and hand calculation for simple box with an area of 144,400 ft^2 and wall resistance of 4 hr-ft^2-^{o}F/Btu

Figure 3 shows that even with a lower resistance value of 4 hr-ft^2-^{o}F/Btu, the ratio of WinAM cooling coil energy to the hand calculation is still 10 to 1. WinAM still outputs a cooling load of 0.031 MMBtu and the hand calculation is still 0.0031 MMBtu for temperatures below 76^{o}F. This means that the resistance of the walls has no effect on the ratio between the hand calculation and the WinAM output at lower temperatures.

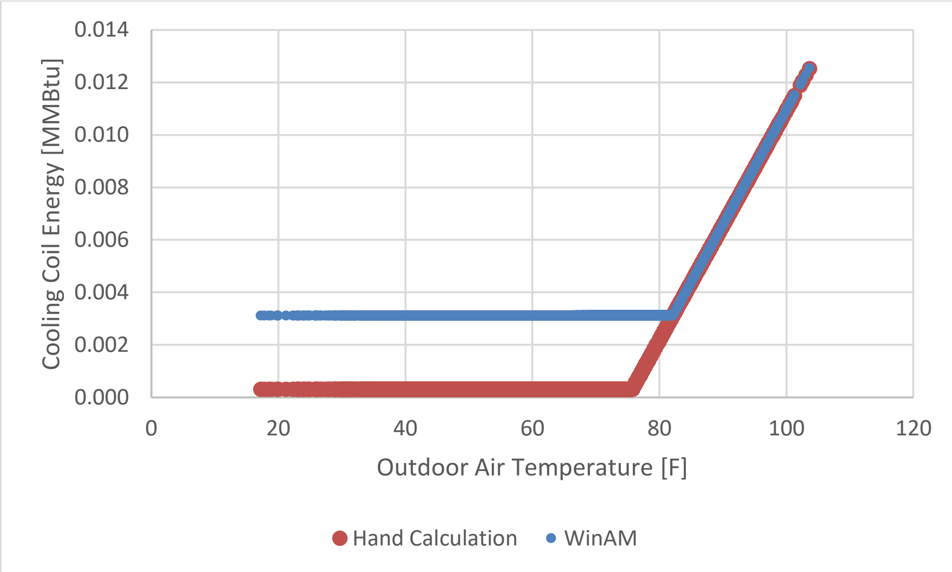

Figure 4: Cooling required for simple box using WinAM and hand calculation for simple box with an area of 14,440 ft^2 and wall resistance of 40 hr-ft^2-^{o}F/Btu

Figure 4 shows the cooling required for both WinAM and the hand calculation with a resistance value of 40 hr-ft^2-^{o}F/Btu and a floor area of 14,440 ft^2. The ratio of cooling coil energy at temperatures below 76^{o}F is still 10 to 1, with WinAM predicting 0.003 MMBtu and the hand calculation predicted 0.0003 MMBtu. This means the floor area is not the cause of the discrepancy between cooling coil energy at temperatures below 76^{o}F.

To determine the cause of this discrepancy, Kevin Christman, a research engineering associate at the Energy Systems Lab, was contacted. Kevin found in the WinAM code that the minimum flow rate does not go below 10% of the design flowrate. This means that although 1% is input for minimum flow, WinAM uses 10% for minimum flow, and the minimum flow used in calculations was 14,440 CFM instead of 1,444 CFM. This ultimately led to a 10 time increase in cooling, as seen in Figures 2-4. Kevin explained that there was a limit set because in most practical cases, the minimum flow will not go below 10%. However, the code has since been updated to allow the minimum flow to go as low as 0.001% for future research purposes. With this update in the code, the hand calculation and WinAM output now match perfectly.

III.II EnergyPlus Input Validation

Once the issue regarding WinAM was resolved, the EnergyPlus outputs needed to be verified with the hand calculations. The same building was used, with important features described in Table 2.

Table 2: Baseline parameters and values

Description	Value
Building Area [ft^2]	144,400
Exterior Zone Percentage [%]	100
T_{CL} [^oF]	55
Outside air [CFM]	0
Window area [%]	0
Wall/roof thermal conductance [Btu/hr-ft^2-^oF]	0.025
Thermal mass	None
People loads [person/ft^2]	0
Lighting loads [W/ft^2]	0
System type	Single duct VAV
Design flow rate [CFM/ft^2]	1
Minimum flow [%]	1
Heating setpoint [^oF]	75
Cooling setpoint [^oF]	75

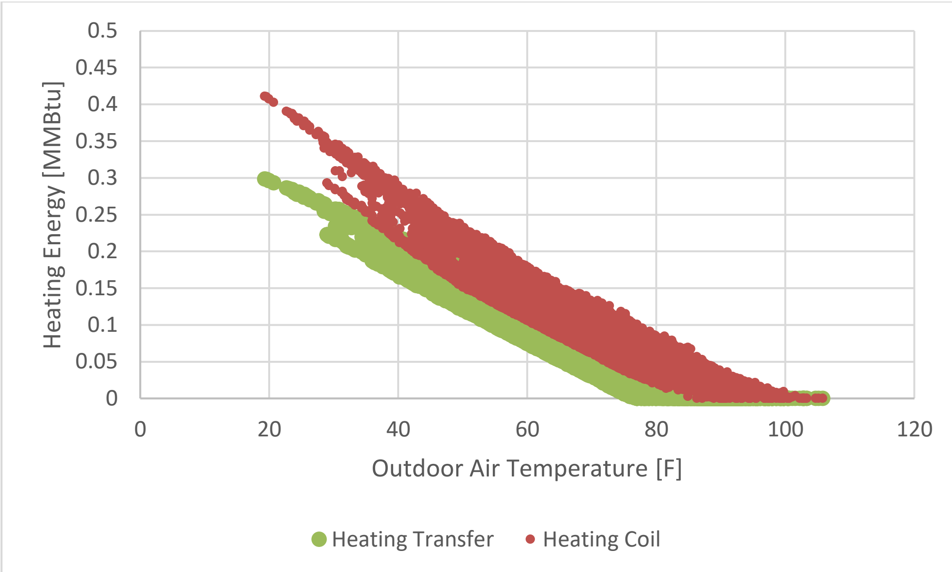

Figure 5: Heating energy transfer versus heating coil energy EnergyPlus output

Figure 5 shows the heating outputs for EnergyPlus. The green represents the heating output called "Heating Energy Transfer," while the red represents "Heating Coil Energy."

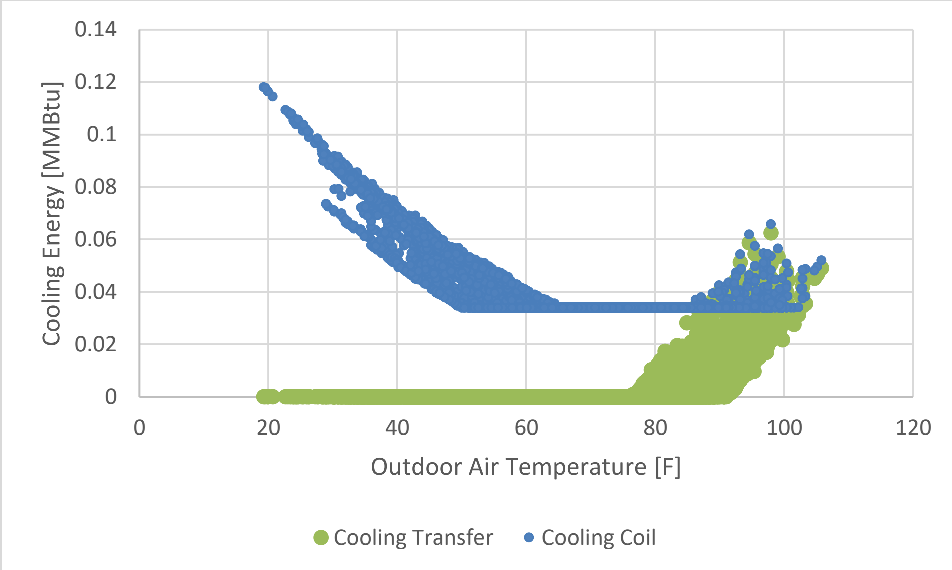

Figure 6: Cooling energy transfer versus cooling coil energy EnergyPlus output

Figure 6 shows the cooling outputs for EnergyPlus. The green represents the heating output called "Cooling Energy Transfer," while the blue represents "Cooling Coil Energy." It is expected the energy transfer for cooling and heating to be equal to the cooling and heating coil energy, respectively. However, the figures above show very different results for the two types of EnergyPlus outputs. The next step is to determine which output is desired; coil energy or energy transfer. The EnergyPlus manual does not give detailed explanations of these outputs, so Dr. Culp, the associate director and manager of the Energy Systems Lab, was approached to decide which output to use. After meeting with him and discussing the project, he said that the coil energy was the output to focus on. This output should be accurately predicting the loads on the cooling and reheat coils. With this known, the next step was to compare the coil loads of

EnergyPlus to the hand calculations. Figures 7 and 8 show this comparison for heating and cooling, respectively.

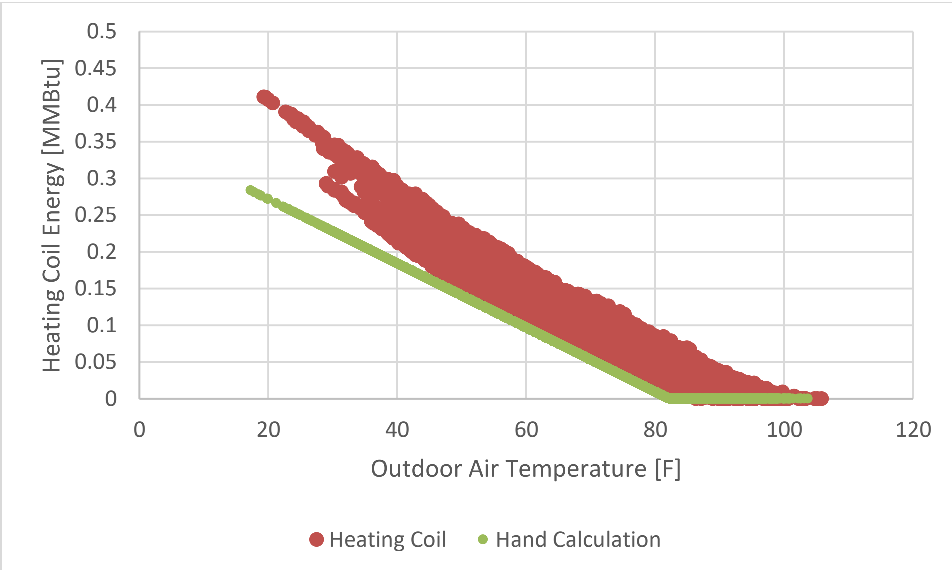

Figure 7: EnergyPlus versus hand calculation heating coil load plotted as a function of outdoor air temperature

Figure 7 shows similar heating predictions, but EnergyPlus is predicting spread in the heating while the hand calculation is predicting a linear relationship between heating coil energy and outdoor air temperature. This spread will be discussed at a later time.

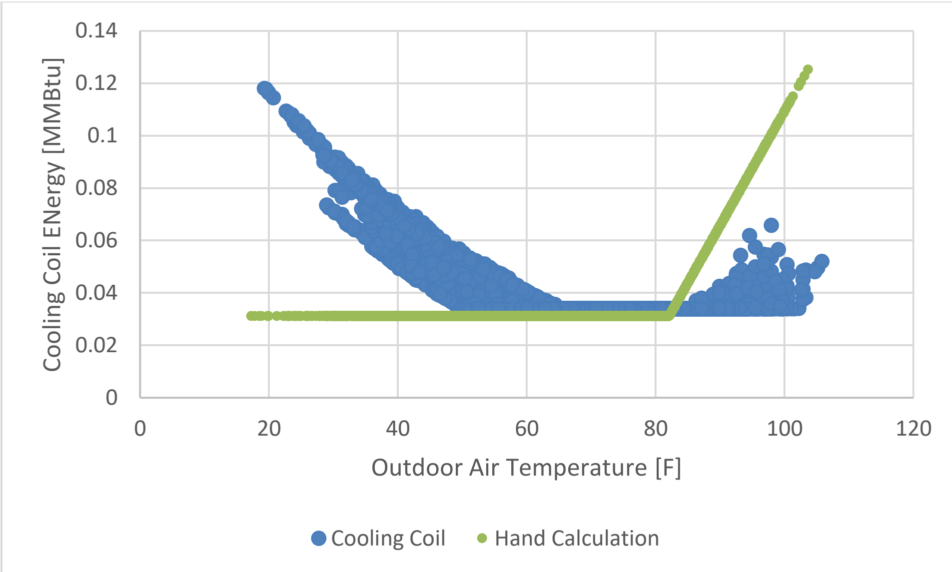

Figure 8: EnergyPlus versus hand calculation cooling coil load plotted as a function of outdoor air temperature

Figure 8 shows EnergyPlus predicting a decrease in cooling as the temperature increases until it is constant, then increasing as temperatures go above 80°F. The hand calculation shows a constant cooling required until the outdoor air temperature goes above 80°F. The main area of concern is the high amounts of cooling used at low temperatures predicted by EnergyPlus. After digging more into EnergyPlus, it was discovered that it has a limit on the Zone Heating Design Supply Air Temperature under the HVACTemplate:Zone:VAV section. This is automatically set to 50°C, or 122°F. It should be noted that this value cannot go above 80°C, or 176°F, without errors occurring in the program; this is likely due to the hot water not being able to heat the air above 176°F. WinAM however, does not have any Heating Supply air temperature limit. Knowing this helped determine the cause of the strange coil behavior at low temperatures.

Because of a temperature limit in EnergyPlus, the flow must increase to meet the zone load in heating mode. This increase in airflow leads to a higher load across the cooling coil as well. After implementing a supply temperature limit in the hand calculations, and making a few minor adjustments to the EnergyPlus inputs, a better match of the outputs was created, as shown in Figures 9 and 10.

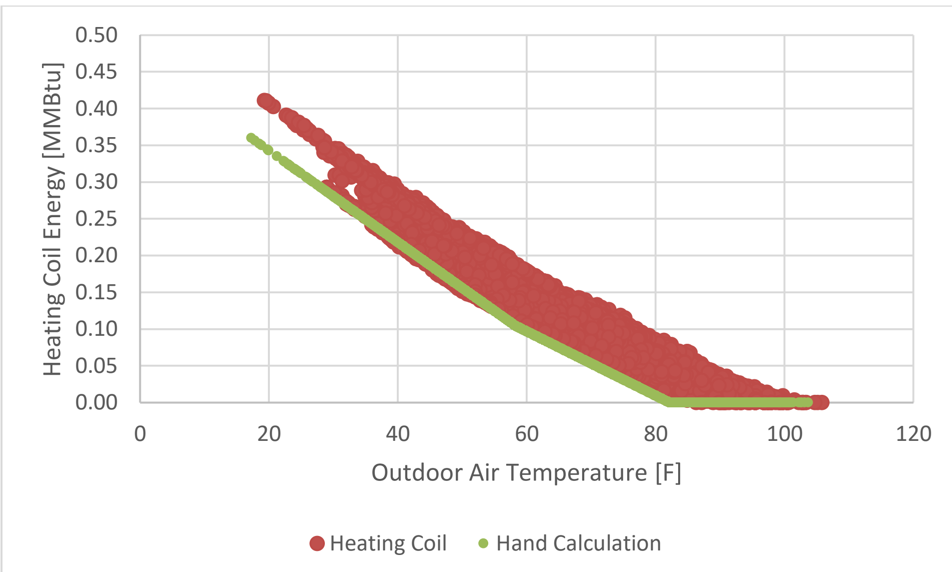

Figure 9: EnergyPlus versus hand calculation heating coil load plotted as a function of outdoor air temperature

Figure 9 shows similar results as Figure 7, with EnergyPlus predicting much more spread in the heating than the hand calculation.

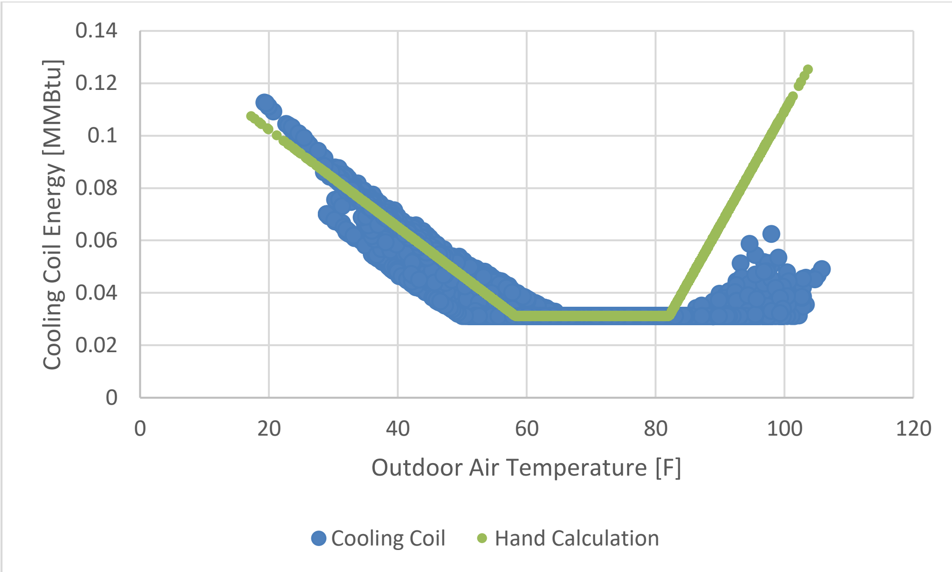

Figure 10: EnergyPlus versus hand calculation cooling coil load plotted as a function of outdoor air temperature

Figure 10 now shows similar trends between EnergyPlus and the hand calculation cooling coil energy. Like the heating, however, EnergyPlus predicts spread in the cooling while the hand calculation does not.

Now that the general trends match, the next step is to address the large amount of spread seen in the EnergyPlus outputs. It is expected for there to be no spread since there is no thermal mass, outside air, or internal loads. One variable at a time was changed in EnergyPlus to determine the cause of the unwanted spread. However, after several days of running the simulations, the problem had not been solved. Luckily, with the help of Michael Witte the problem was identified. He was able to look at the EnergyPlus file and discover various changes that could be made to fix the problem. One of those dealt with the thermal absorptance of the walls. In Material:NoMass section of the EnergyPlus input, the thermal absorptance is described as “the fraction of incident long wavelength radiation that is absorbed by the material” (LLC, Big Ladder Software, 2018). The range of values is between zero and one. I understood this to mean a value of one represented a wall that would absorb and transfer all thermal loads, leading to a better representation of a massless material. However, Michael Witte explained that the value should be equal to zero because this will effectively turn off radiant exchange, eliminating all thermal storage effects. The results from changing this single value are shown in Figures 11 and 12. It should be noted that for these results, the Heating Zone Supply Air Temperature was increased from 50^{o}C to 80^{o}C from previous results in both EnergyPlus and the Hand calculations.

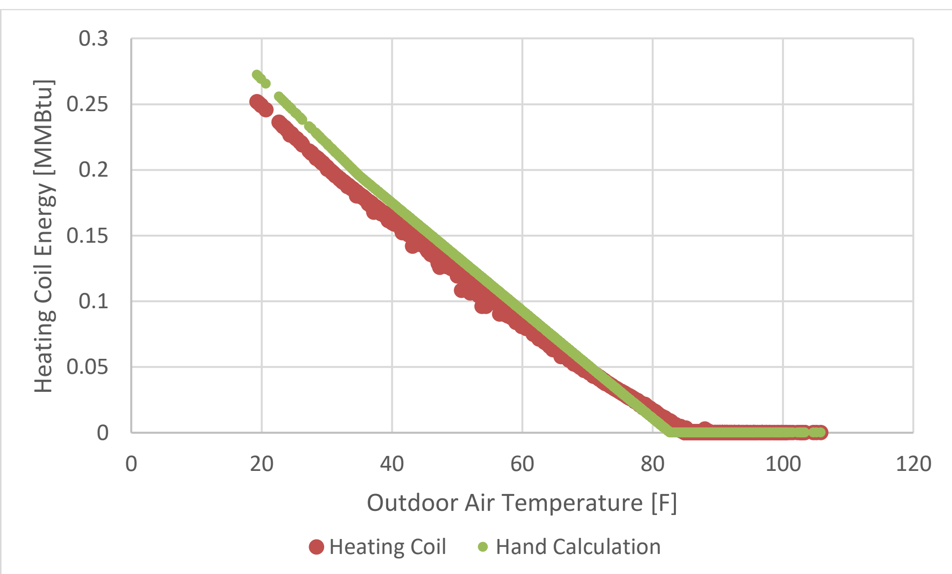

Figure 11: EnergyPlus versus hand calculation heating coil load plotted as a function of outdoor air temperature

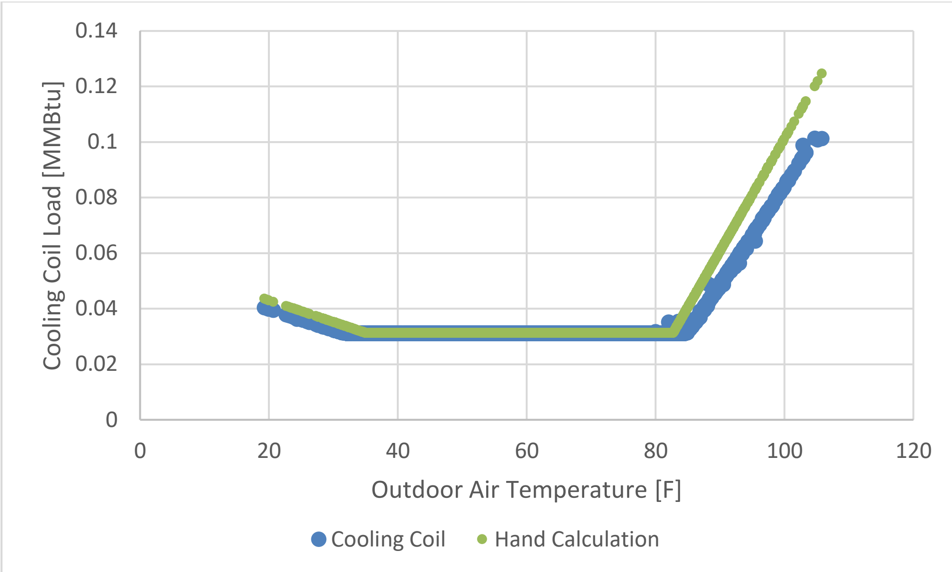

Figure 12: EnergyPlus versus hand calculation cooling coil load plotted as a function of outdoor air temperature

Figures 11 and 12 now show very little spread in the load output for EnergyPlus. However, a new issue arises looking at the low and high ends of temperature. The process into determining the cause of this discrepancy will be discussed in the next section.

III.III EnergyPlus Surface Coefficients

This section covers the issues of matching the hand calculation with the EnergyPlus coil load output at the low and high ends of the temperature range. To determine where the issue was coming from, each step of the hand calculation was compared to the output of EnergyPlus. By doing this, it was determined that the conduction values through the walls were lower for

EnergyPlus than the hand calculation. Area and the temperature difference are exact matches for the hand calculation and EnergyPlus input, so it was concluded that the problem was linked to the resistance value of the wall. Since the wall resistance value inputs matched for EnergyPlus and the hand calculation, the only explanation for the discrepancy was inside and outside surface coefficients. If no input for these values is given for EnergyPlus, a default algorithm is used to calculate the surface coefficients based on the weather data. These default values of surface coefficients were plotted to determine how they behave as a function of temperature.

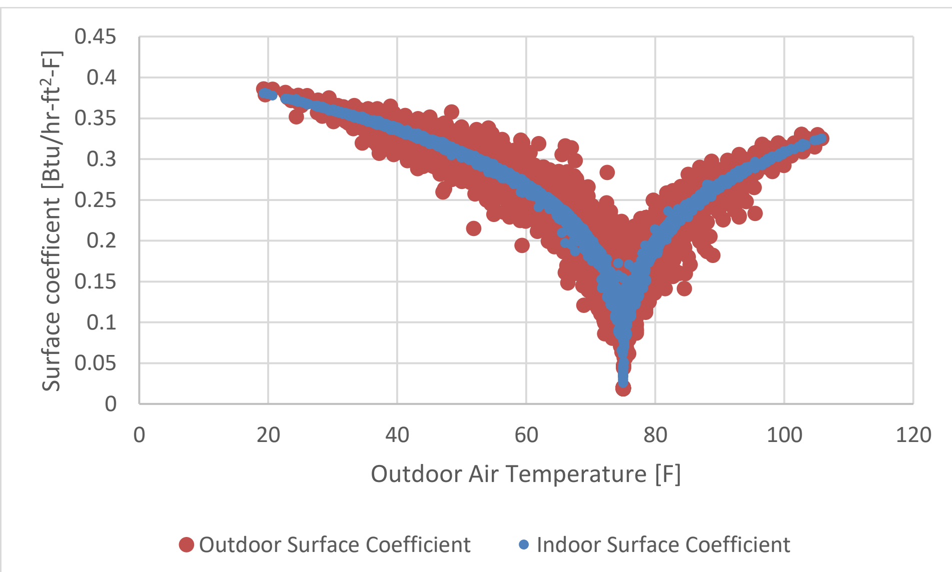

Figure 13: Indoor and outdoor surface coefficients of the walls as a function of outdoor air temperature

Figure 13 shows the surface heat transfer coefficients ranging from roughly 0.03 Btu/hr-ft^2-°F to 0.4 Btu/hr-ft^2-°F. According to Table 1 of the Thermal and Water Vapor Transmission Data section of the ASHRAE Fundamentals handbook (ASHRAE Handbook: Fundamentals, 1999), a constant indoor surface coefficient of around 1.46 Btu/hr-ft^2-°F and an outdoor surface coefficient of 4.0 Btu/hr-ft^2-°F in summer and 6.0 Btu/hr-ft^2-°F in winter are expected. The EnergyPlus output however shows a large departure from these expected values. Mike Witte was contacted again to gain some insight into EnergyPlus surface coefficient values. He explained that EnergyPlus uses an algorithm to calculate the surface coefficient values as a function of temperature and wind speed given from weather data, explaining why the values are not constant as given in ASHRAE. He also noted that the surface coefficient value can be fixed as constant using SurfaceProperty:ConvectionCoefficients for the inside and outside surfaces. Mike suggested setting the surface coefficient to 176 Btu/hr-ft^2-°F (1000 W/m^2-K) so that the resistance due to the surface coefficients is negligible. It should be noted that the value of 176 Btu/hr-ft^2-°F (1000 W/m^2-K) is not a realistic value and was only used in this case to match the desired wall resistance of the hand calculation. More realistic values are used in future models. Changing this value allows for the overall resistance of the wall to match the input of the hand calculation and solve the discrepancy of the coil load outputs. Figures 14 and 15 show the new EnergyPlus output with the updated surface coefficient values compared to the hand calculation.

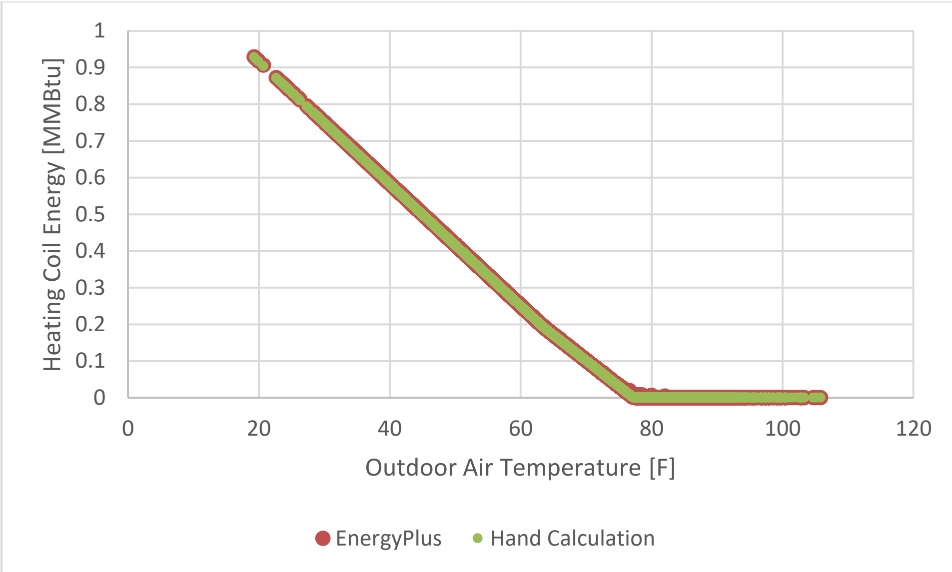

Figure 14: EnergyPlus heating coil load versus hand calculation load for a resistance of 12.5 hr-ft^2-^{o}F/Btu

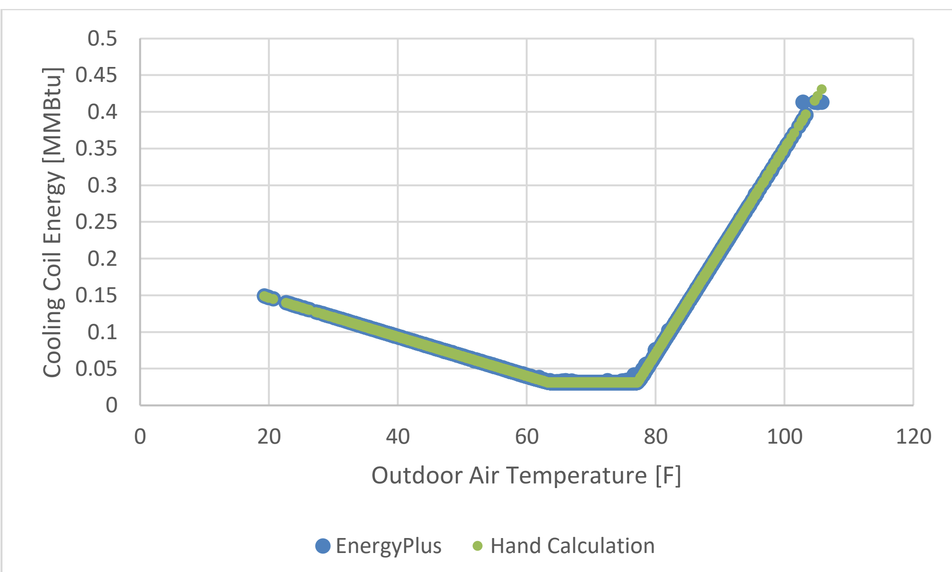

Figure 15: EnergyPlus cooling coil load versus hand calculation load for a resistance of 12.5 hr-ft^2-^{o}F/Btu

With the surface coefficients set to a constant value, the hand calculation and EnergyPlus output for heating and cooling now match nearly perfectly. With the heating and cooling coil energy outputs of the hand calculation and EnergyPlus matching, WinAM outputs could now be added for comparison.

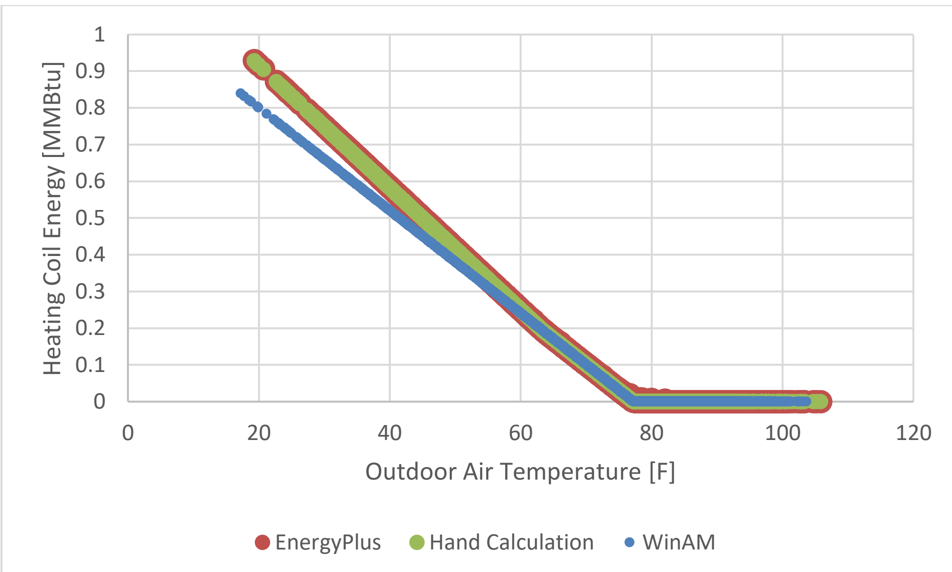

Figure 16: Heating coil energy output for EnergyPlus, hand calculation, and WinAM with 1% minimum flowrate

Figure 16 shows the heating coil energy consumption for EnergyPlus, WinAM, and the hand calculation.

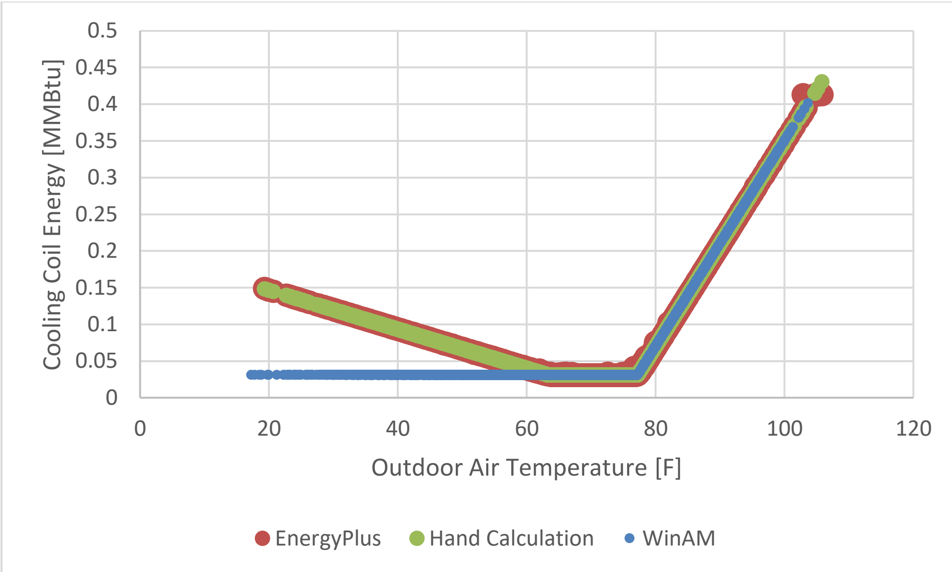

Figure 17: Cooling coil energy output for EnergyPlus, hand calculation, and WinAM with 1% minimum flowrate

Figure 17 shows cooling coil energy consumption for EnergyPlus, WinAM, and the hand calculation.

These figures illustrate that the hand calculation and EnergyPlus outputs are identical, meaning the inputs of EnergyPlus are likely correct for the simple box, and EnergyPlus is behaving as expected. At temperatures above 60°F, the WinAM outputs are also identical to the hand calculation and EnergyPlus but differ below 60°F for both heating and cooling. This discrepancy is due to the heating supply temperature setpoint. In WinAM, the manual states, "WinAM dynamically modulates reheat coils to meet space loads and thus doesn't need user-supplied setpoint schedules." (WinAM 5.2, 2018). There is no heating supply temperature limit on WinAM, so the supply temperature goes as high as it needs to meet the loads. In EnergyPlus, however, this supply temperature is limited to 175°F. Because of this limit, more airflow is needed to meet the space loads, leading to an increase in both cooling and heating coil energy for EnergyPlus. A heating supply temperature limit of 175°F was used in the hand calculation.

The divergence of WinAM at lower temperatures can be corrected by raising the minimum flow rate from 1% to 30%. Raising the minimum flowrate allows EnergyPlus to meet the heating load at a lower supply temperature and eliminates the need to increase the total flowrate of the system.

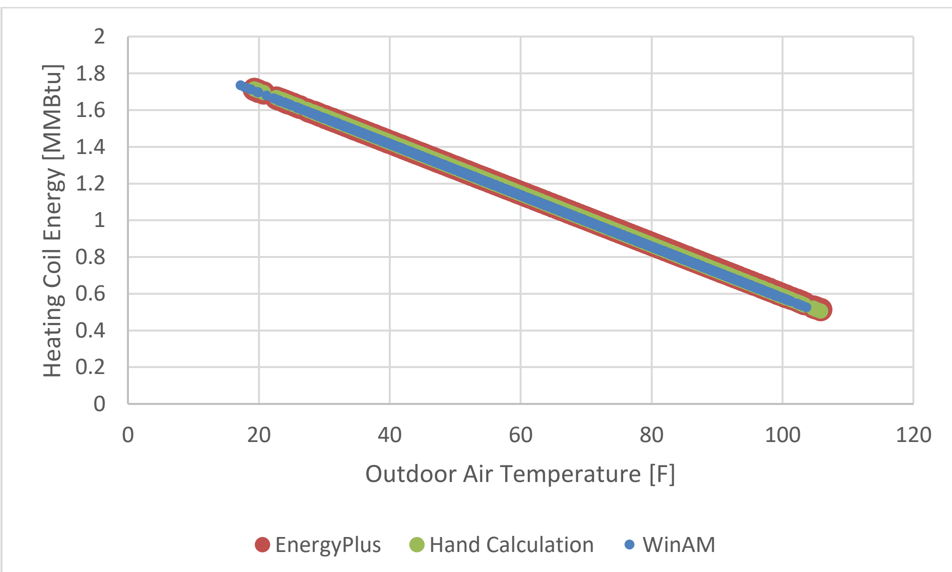

Figure 18: Heating coil energy output for EnergyPlus, hand calculation, and WinAM with 30% minimum flowrate

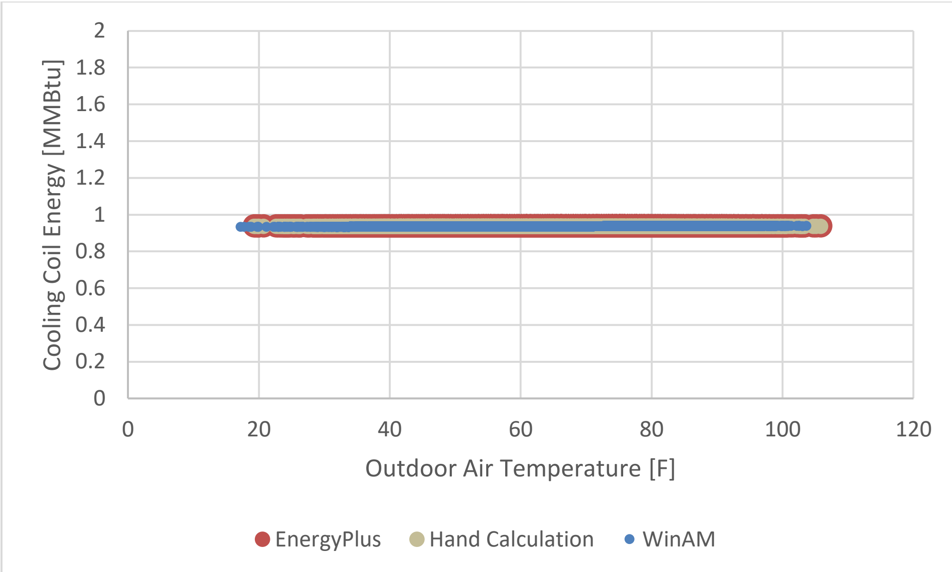

Figure 19: Cooling coil energy output for EnergyPlus, hand calculation, and WinAM with 30% minimum flowrate

Figures 18 and 19 represent the heating and cooling coil energy for EnergyPlus, a hand calculation, and WinAM at 30% minimum flow, respectively. These figures now show equal outputs between the three modeling tools, verifying the inputs for EnergyPlus and WinAM. The simple box validation is important for future modeling. This simple box model can now be used as a baseline for all future models and confirms that the EnergyPlus and WinAM inputs are correct and the simulations tools are behaving as expected.

CHAPTER IV

THERMAL MASS EFFECTS

This section describes the process of building up the validated simple box one parameter at a time to see how each parameter effects the output of EnergyPlus and WinAM. The goal of this is to slowly create a more realistic building while also determining which parameters are the most influential for both simulation programs. The baseline case of building being model is the same as the previous section. This baseline can be labeled as Run 1. Table 3 is a copy of Table 2 and has been placed in this section for convenience.

Table 3: Baseline parameters and values, copy of Table 2

Description	Value
Building Area [ft^2]	144,400
Exterior Zone Percentage [%]	100
Outside air [CFM]	0
Window area [%]	0
Wall/roof thermal conductance [Btu/hr-ft^2-^oF]	0.025
Thermal mass	None
People loads [person/ft^2]	0
Lighting loads [W/ft^2]	0
System type	Single duct VAV
Design flow rate [CFM/ft^2]	1
Minimum flowrate [%]	1
Heating setpoint [^oF]	75
Cooling setpoint [^oF]	75

Table 4: List of changes for each run added to baseline simple box

Run	Parameters Changed	New Value
2	Lighting load [W/ft^2]	1
	People load [people/ft^2]	0.005
3	Minimum flowrate [%]	30
4	Outdoor Air flowrate [CFM/ft^2]	0.085
5	Heating setpoint [^{o}F]	72
	Cooling setpoint [^{o}F]	75
6	Thermal mass	yes
	Wall and Roof resistance [hr-ft^2-^{o}F/Btu]	12.37

Table 4 lists the next several models created, labeled as runs, and highlights the parameter that was changed. Each run modifies one parameter from the previous run, with run 2 changing the lighting and people loads from the baseline simple box discussed in the previous section. The lighting load of 1 W/ft^2 is an arbitrary number chosen that is often used as an initial estimation of an office building lighting usage. Both the people load value of 0.005 people/ft^2 and the outdoor air flowrate came from ASHRAE 62.1 standard (ASHRAE 62.1, 2010). Table 6-1 from ASHRAE 62.1 lists for an office space 5 CFM/person, 0.06 CFM/ft^2, and 1 person/200 ft^2. That means for the building being simulated, there are 500 people, 2500 CFM outdoor air rate due to occupancy, 6000 CFM outdoor air rate due to area, totaling 8500 CFM or 0.085 CFM/ft^2. The heating and cooling setpoints and the wall and roof resistance values were also chosen arbitrarily based on typical values seen in the field. The wall construction is made up of brick, heavyweight concrete, insulation, and gypsum, giving a thermal mass, or thermal capacitance of around 665,000 Btu/hr-^{o}F (700,000 kJ/K).

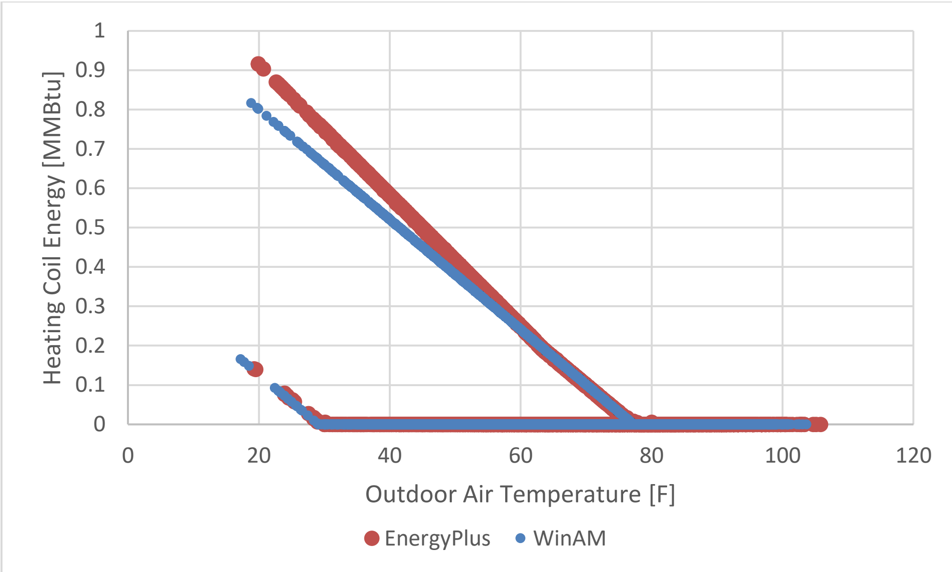

Figure 20: Run 2 (new internal loads) heating consumption of EnergyPlus and WinAM

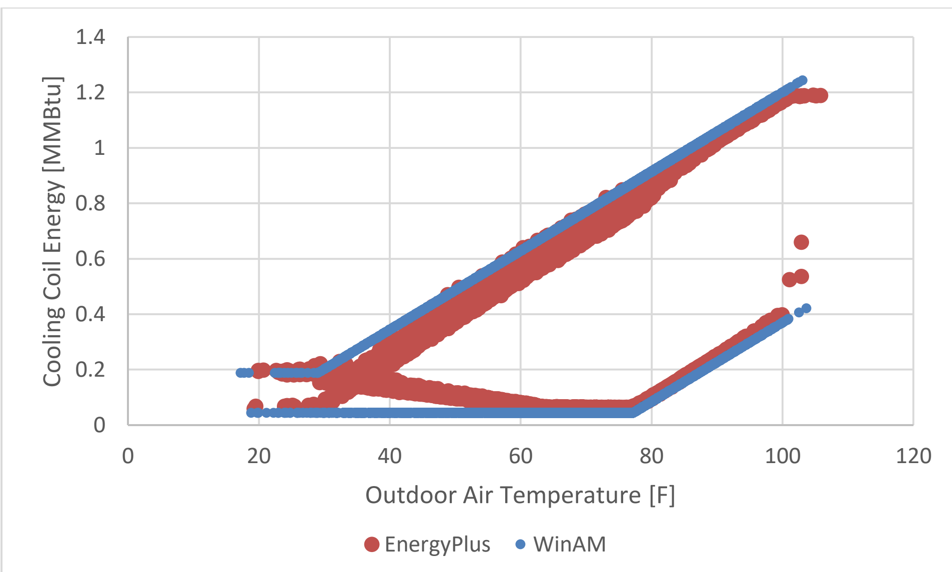

Figure 21: Run 2 (new internal loads) cooling consumption of EnergyPlus and WinAM

Figure 20 shows the heating coil energy of WinAM and EnergyPlus for run 2; Figure 21 shows the cooling coil energy of WinAM and EnergyPlus for run 2. Run 2 adds lighting and people loads to the baseline model. Comparing to the baseline, Figures 20 and 21 reveal decreased heating and increased cooling. This is because of the additional heat added to the zone due to internal loads. It should be noted that similar to the baseline model, the heating at low temperature does not match for EnergyPlus and WinAM. This is again due to the limited supply temperature of EnergyPlus. This issue can be resolved in the same way as the baseline by increasing the minimum flow, which was done in the next run.

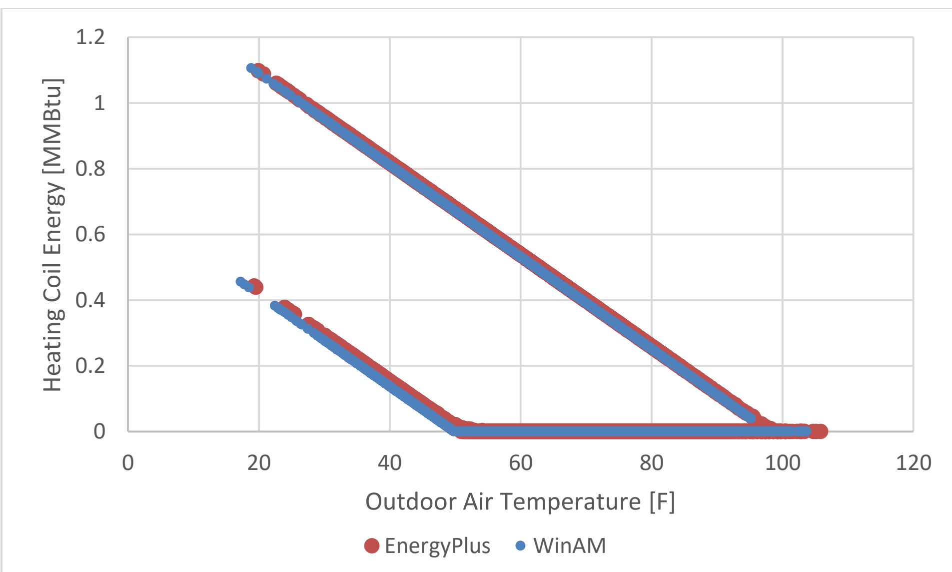

Figure 22: Run 3 (increased minimum flowrate) heating consumption of EnergyPlus and WinAM

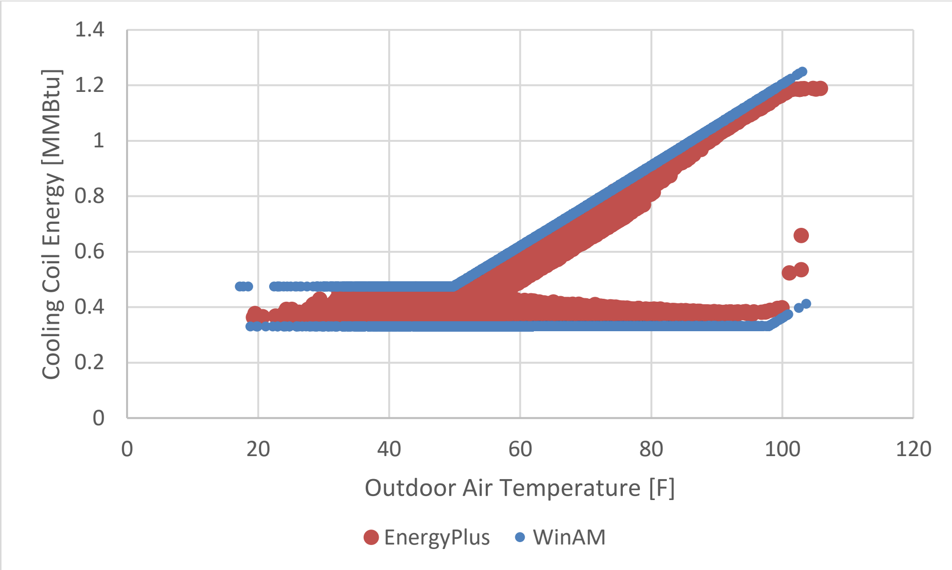

Figure 23: Run 3 (increased minimum flowrate) cooling consumption of EnergyPlus and WinAM

Figures 22 and 23 show the heating and cooling coil energy for WinAM and EnergyPlus respectively. As mentioned above, run 3 increases the minimum flow of run 2 from 1% to 30%. All other parameters are unchanged. Figure 22 shows a nearly perfect match for heating. The percent difference between WinAM and EnergyPlus annual heating coil energy for this run is 2.18%. The percent difference between WinAM and EnergyPlus annual cooling coil energy is 2.67%.

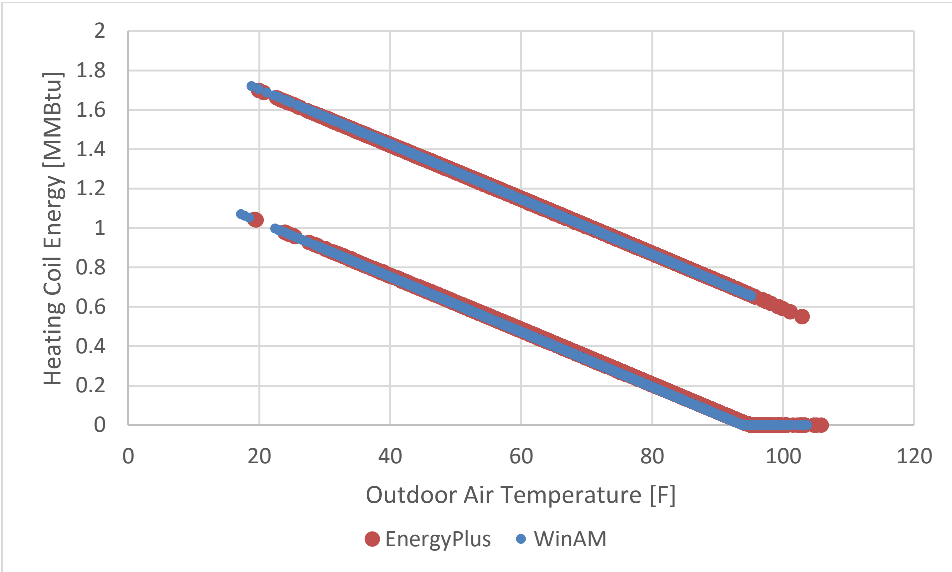

Figure 24: Run 4 (increased outdoor air) heating consumption of EnergyPlus and WinAM

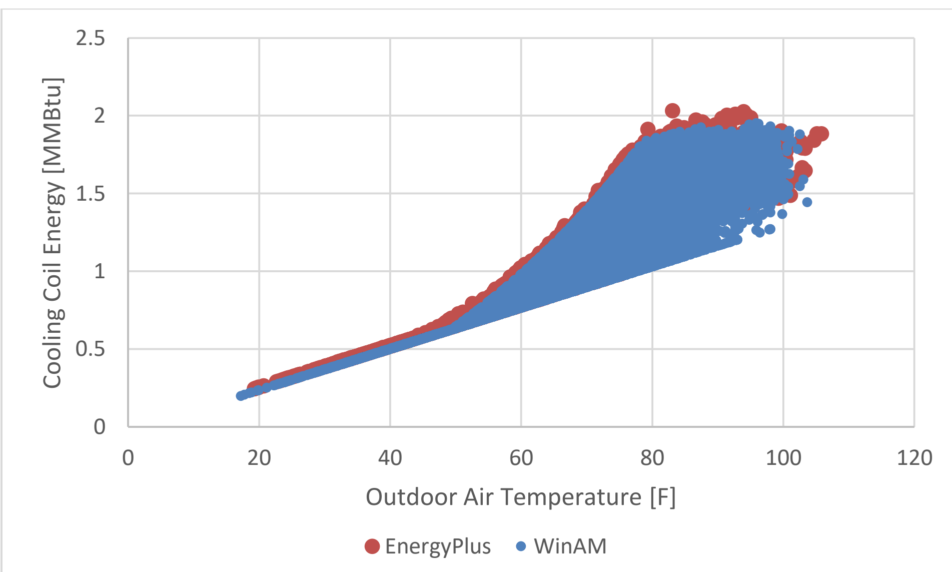

Figure 25: Run 4 (increased outdoor air) cooling consumption of EnergyPlus and WinAM

Figures 24 and 25 show the heating and cooling coil energy for WinAM and EnergyPlus respectively. Run 4 added outdoor air to run 3. The amount of outdoor air added is 0.085 CFM/ft^2, which was calculated using ASHRAE Standard 62.1. Outdoor air temperature is variable over the day, leading to the large spread in Figure 25. For this run, the percent difference between WinAM and EnergyPlus is 2.55% for annual cooling coil energy and 0.42% for annual heating coil energy. These values are small and indicate that outdoor air addition does not intensify inaccuracies in WinAM due to its simplified computing.

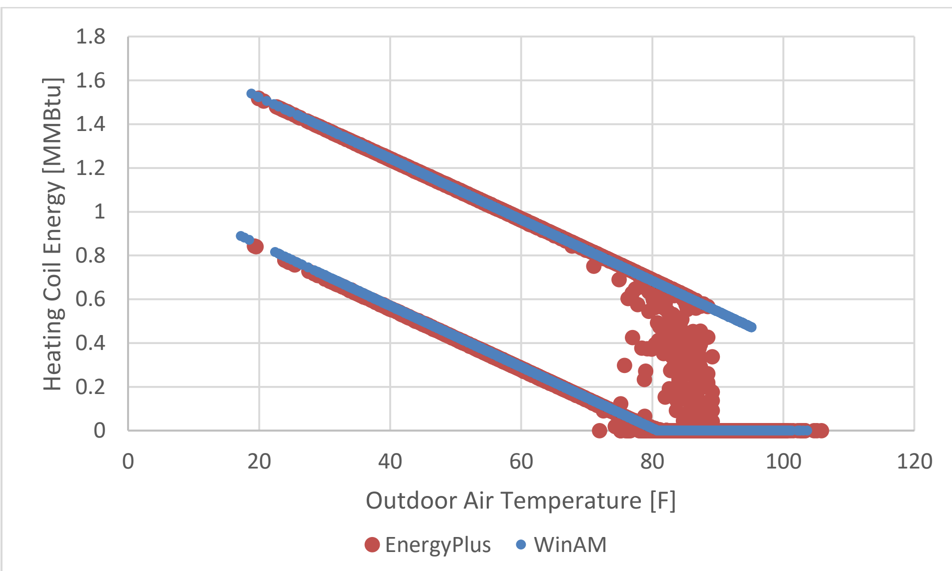

Figure 26: Run 5 (new heating setpoint) heating consumption of EnergyPlus and WinAM

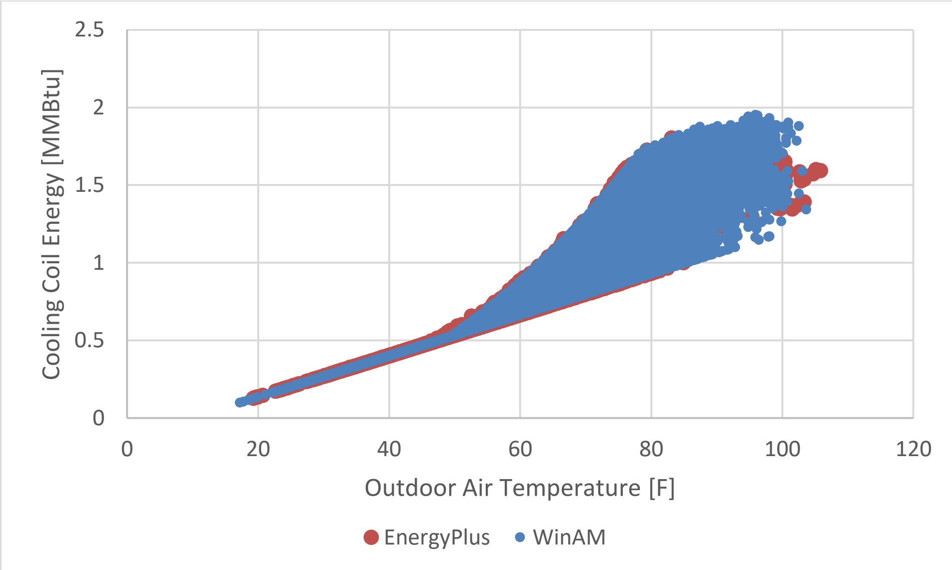

Figure 27: Run 5 (new heating setpoint) cooling consumption of EnergyPlus and WinAM

Figures 26 and 27 show the heating and cooling coil energy for WinAM and EnergyPlus respectively. Run 5 incorporates separate heating and cooling setpoints. The implementation of a lower heating temperature setpoint leads to a small reduction in both heating and cooling for all temperatures, as seen when comparing Figures 24 and 25. The percent difference between EnergyPlus and WinAM for annual cooling coil energy is 0.56%. Points between the smooth lines in heating is likely due to hours not being met. There is a process in the code of EnergyPlus that causes the supply flowrate to ramp up when the zone is not meeting the required setpoint. This process should be further investigated in the future. However, despite this peculiarity in EnergyPlus, the percent difference between EnergyPlus and WinAM for annual heating is only 3.8%. This means the strange computation of EnergyPlus that leads to these undesirable points does not lead to significant difference in annual consumption from WinAM. It should be noted that EnergyPlus will have unmet hours for any difference in heating and cooling setpoints, despite how small the difference is. For example, EnergyPlus will still have the undesirable points due to the ramping up of the supply flowrate if the cooling setpoint is 75^{o}F and the heating setpoint is 74.9^{o}F. This reveals that when the system switches from heating to cooling mode, EnergyPlus counts that hour as not meeting the required setpoint temperature due to transient effects delaying the zone from reaching the new setpoint. This in turn causes EnergyPlus to increase the supply flowrate for one hour to meet the new load. This is likely a bug in EnergyPlus that will be discussed with Michael Witte in future work.

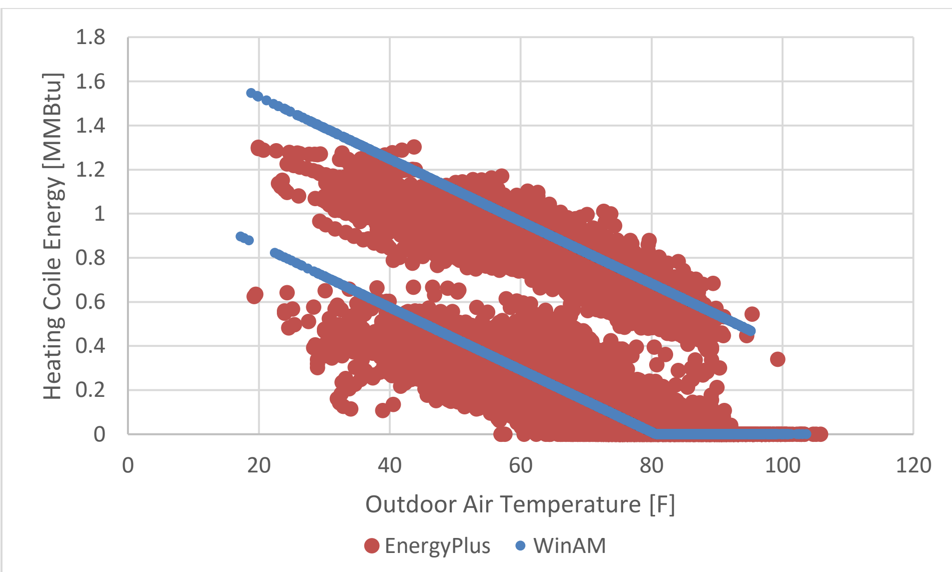

Figure 28: Run 6 (added thermal mass) heating consumption of EnergyPlus and WinAM

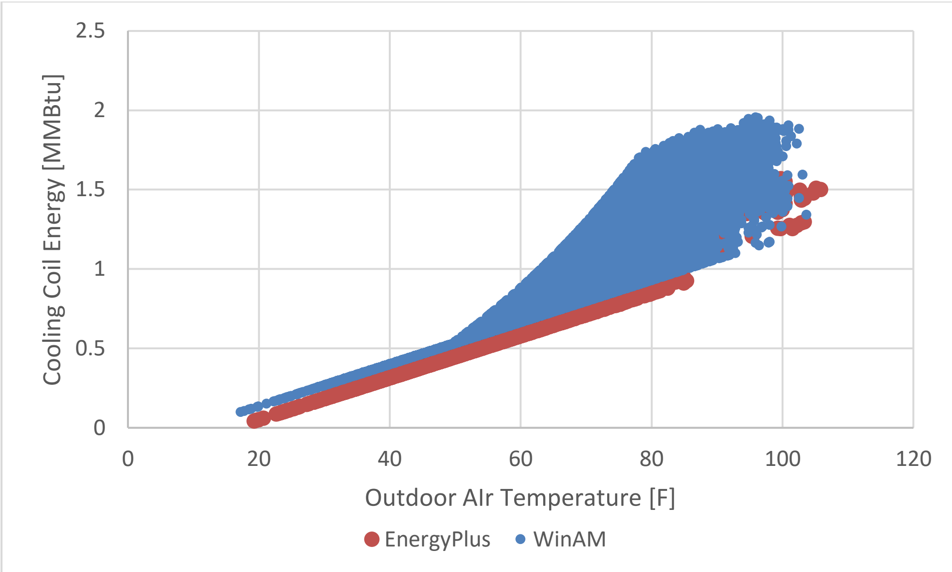

Figure 29: Run 6 (added thermal mass) cooling consumption of EnergyPlus and WinAM

Figure 28 represents the predicted heating coil load for the simple box with the parameters listed in run 6 shown in Table 4. This run added thermal mass to the simple box. Figure 28 shows there is still a good match in the predicted heating load for WinAM and EnergyPlus, but a larger difference in the cooling coil load shown in Figure 29. The percent difference revealed WinAM overpredicting annual cooling consumptions by 10% and overpredicting annual heating consumption by 15%. This difference is caused by thermal mass and will be further investigated in this research. A new, more realistic building will be modeled with varying wall constructions to better understand how thermal mass effects a building with setbacks and how WinAM can improve its energy estimations without heavy computing.

Next, the EnergyPlus daily consumption data from run 6 was used in WinAM as measured utility data. This was done to see how WinAM calibrates to the EnergyPlus prediction.

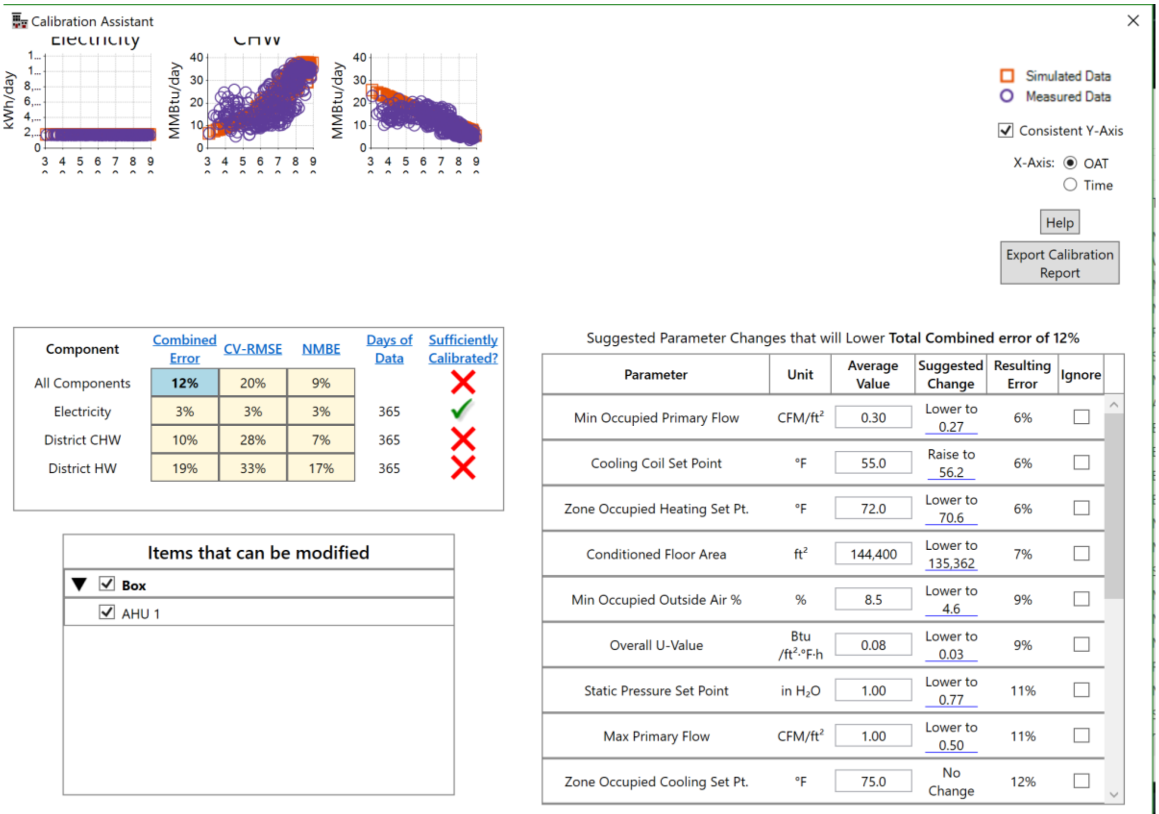

Figure 30: Initial calibration report from WinAM

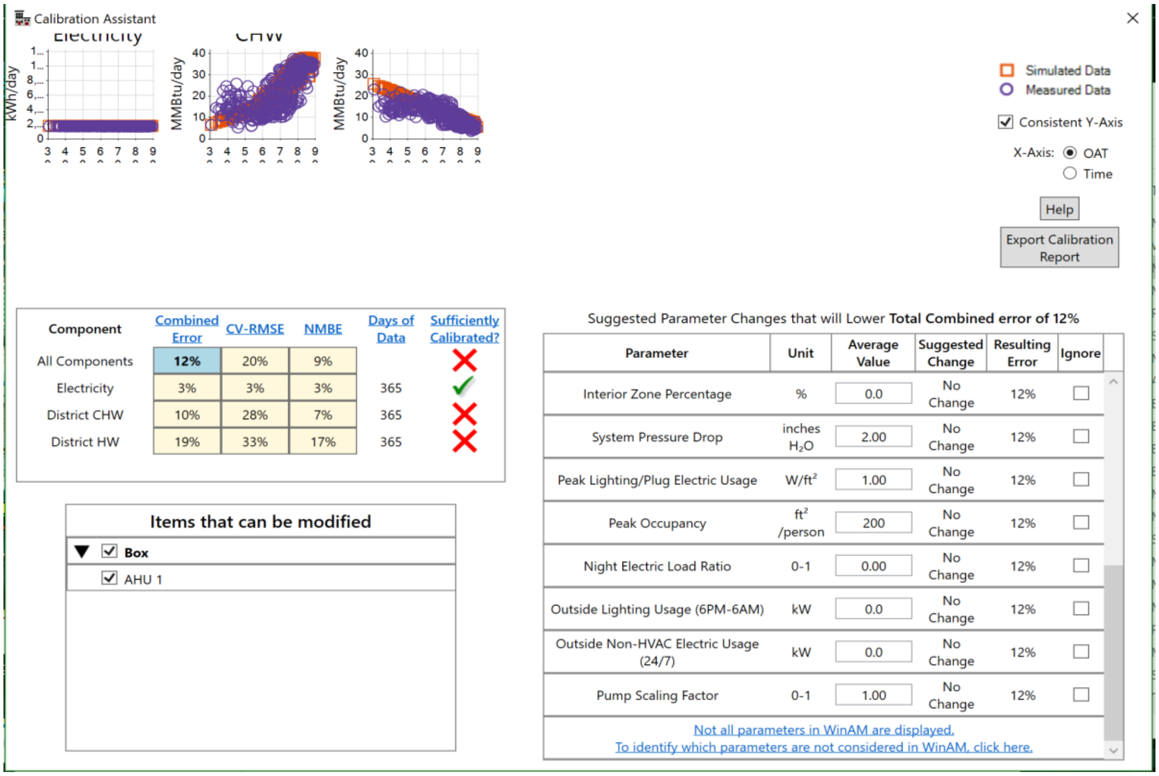

Figure 31: Continued initial calibration report from WinAM

Figures 30 and 31 show the calibration pages of WinAM. Using daily consumption data, the error of the model in predicting consumption components now ranges from 3% to 19%. Figures 33 and 34 also show the parameters that can be changed to reduce the error of the model. In this calibration process, the cooling coil set point was raised from 55°F to 56.2°F. The calibration assistant then recommended lowering the overall U-value from 0.08 Btu/hr-ft^2-°F to 0.05 Btu/hr-ft^2-°F. This indicates that the effect of the thermal mass on building consumption can be viewed as effectively lowering the U-value in a steady-state calculation. After the U-value was decreased, the model still had errors above 5% which is considered too high to be properly calibrated.

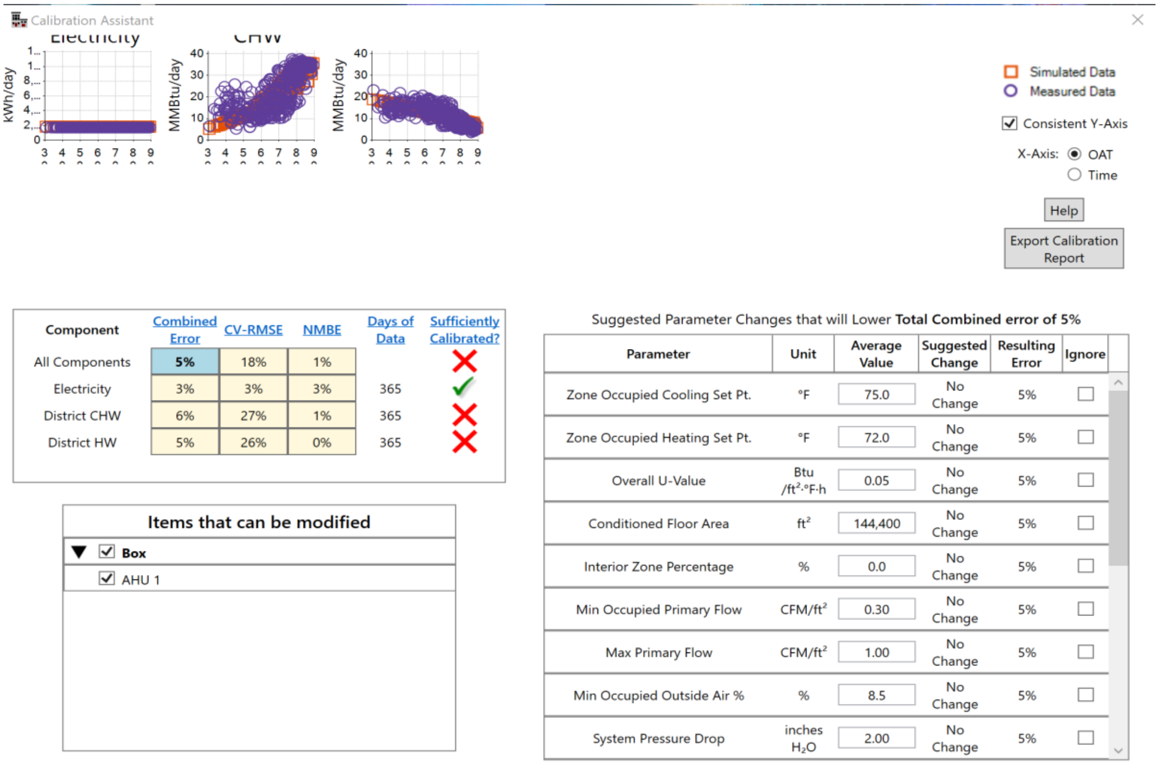

Figure 32: Final calibration report from WinAM

Figure 32 shows the final calibration page after all available changes were made. After calibration, the simulation still had combined error values for individual consumption components ranging from 3% to 6%, and a 5% combined error for all components. However, after observing the measured data, it was discovered that WinAM was not accurately depicting the EnergyPlus output data.

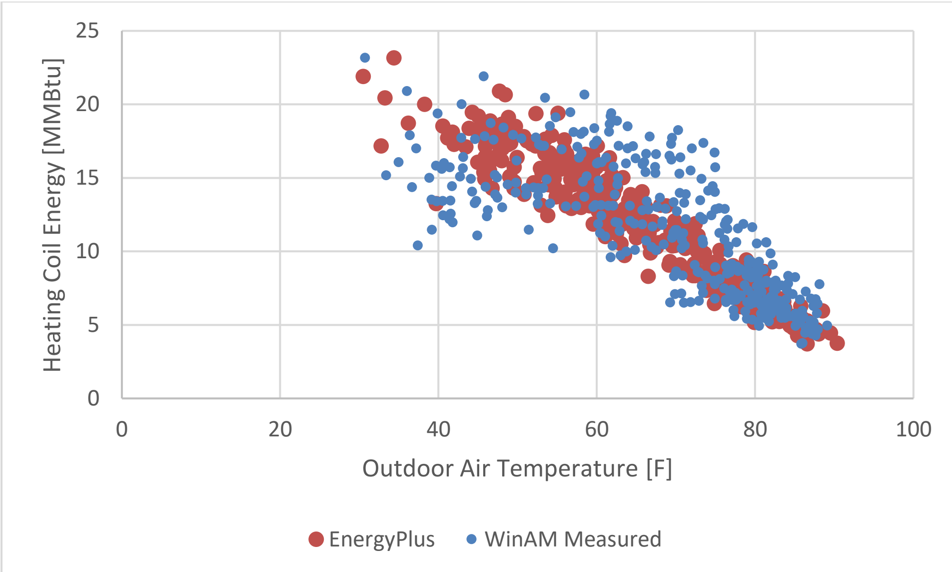

Figure 33: Original EnergyPlus heating coil energy versus WinAM reformatted measure heating coil energy

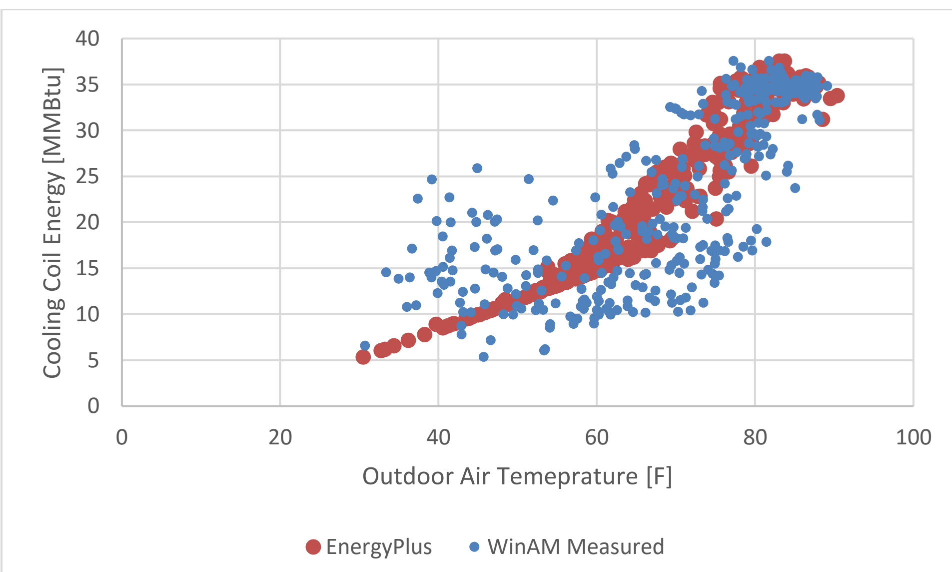

Figure 34: Original EnergyPlus cooling coil energy versus WinAM reformatted measure cooling coil energy

Figures 33 and 34 represent the daily EnergyPlus heating and cooling coil energy, respectively. The red points are the direct coil EnergyPlus output; the blue points are the new output created by WinAM after inputting the EnergyPlus consumption data into the WinAM metered data template. This is referred to as the "reformatted measure" in the figure titles. The figures show a large difference in the two measurements, despite them being the same consumption data from EnergyPlus. This problem occurs because the WinAM measured data consumption asks for consumption on a time scale, rather than a temperature scale. EnergyPlus uses a different weather file than WinAM, leading to a discrepancy in the daily consumption. For example, on January 1st, the EnergyPlus weather file uses an outdoor dry bulb temperature of 51^{o}F, while WinAM uses 41^{o}F. This means that WinAM uses 41^{o}F for January 1st dry bulb temperature for the EnergyPlus heating and coil energy value that was calculated using 51^{o}F.

To fix this issue, the hourly weather information from EnergyPlus was reformatted and input into WinAM as a new weather file. Now, each day has the same average temperature for both WinAM and EnergyPlus and allows for a more accurate daily calibration. Figure 35 shows the new daily heating and cooling coil energy outputs for EnergyPlus and the reformatted WinAM metered consumption.

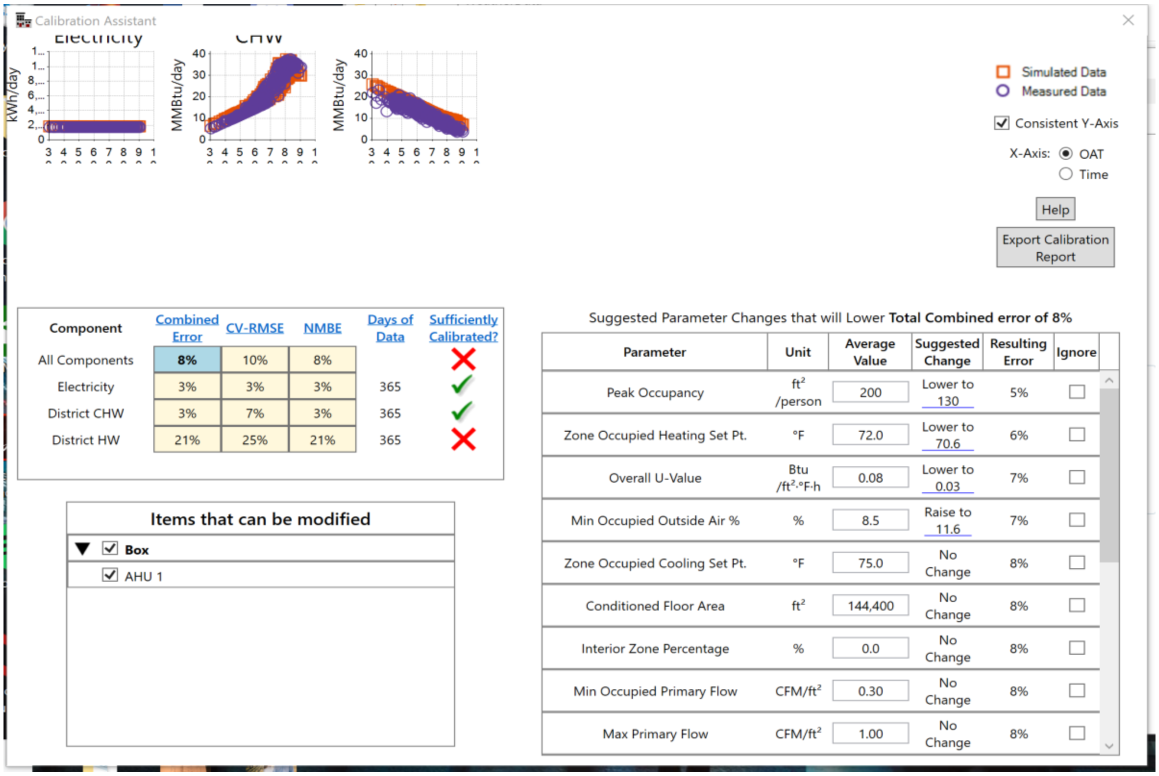

Figure 35: Initial calibration report in WinAM

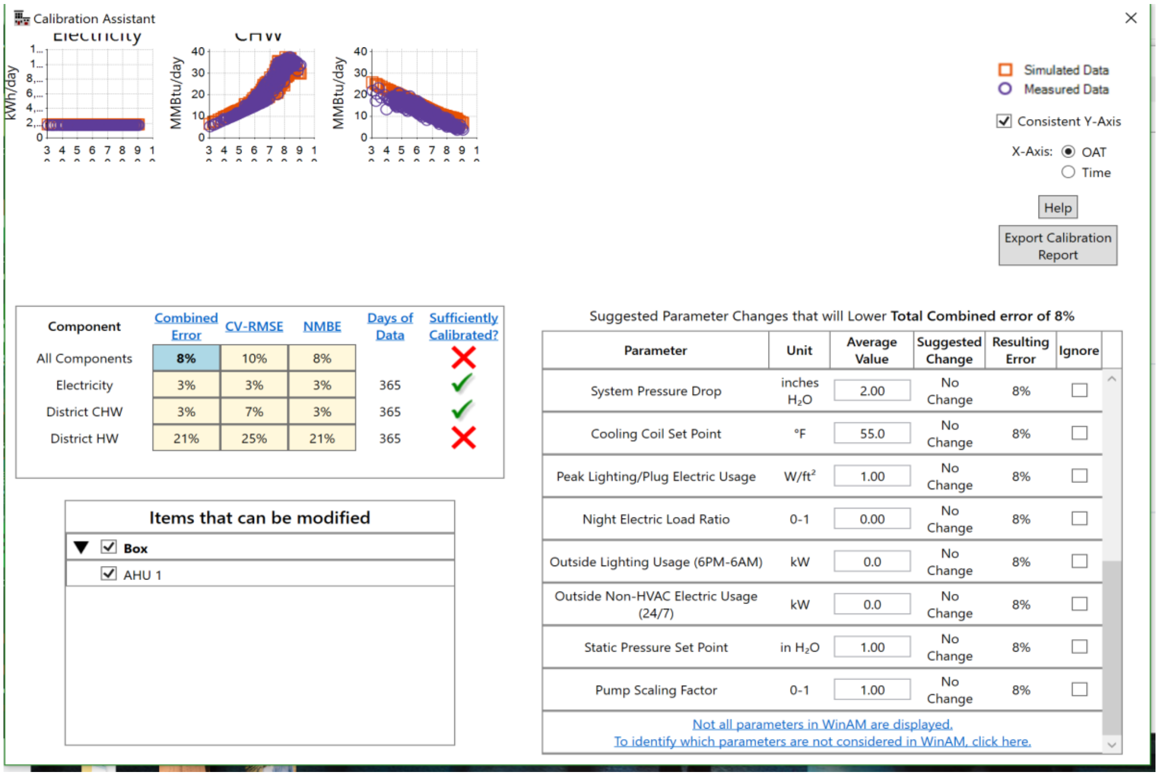

Figure 36: Continued initial calibration report in WinAM

Figures 35 and 36 show the calibration pages of WinAM. Using EnergyPlus daily consumption data, the combined error of the modeled consumption components ranges from 8% to 21%. Figures 35 and 36 also show the parameters that can be changed to reduce the error of the model. In this calibration process, the outdoor air percentage was raised from 8.5% to 11.6%, the zone heating setpoint was lowered from 72°F to 70°F, and the cooling coil setpoint was lowered from 55°F to 54.3°F. The increase in outdoor air leads to decrease in cooling at cold temperatures and an increase of cooling at high temperatures. A lower heating setpoint leads to less reheat and lowering the cooling coil setpoint leads to higher cooling consumption.

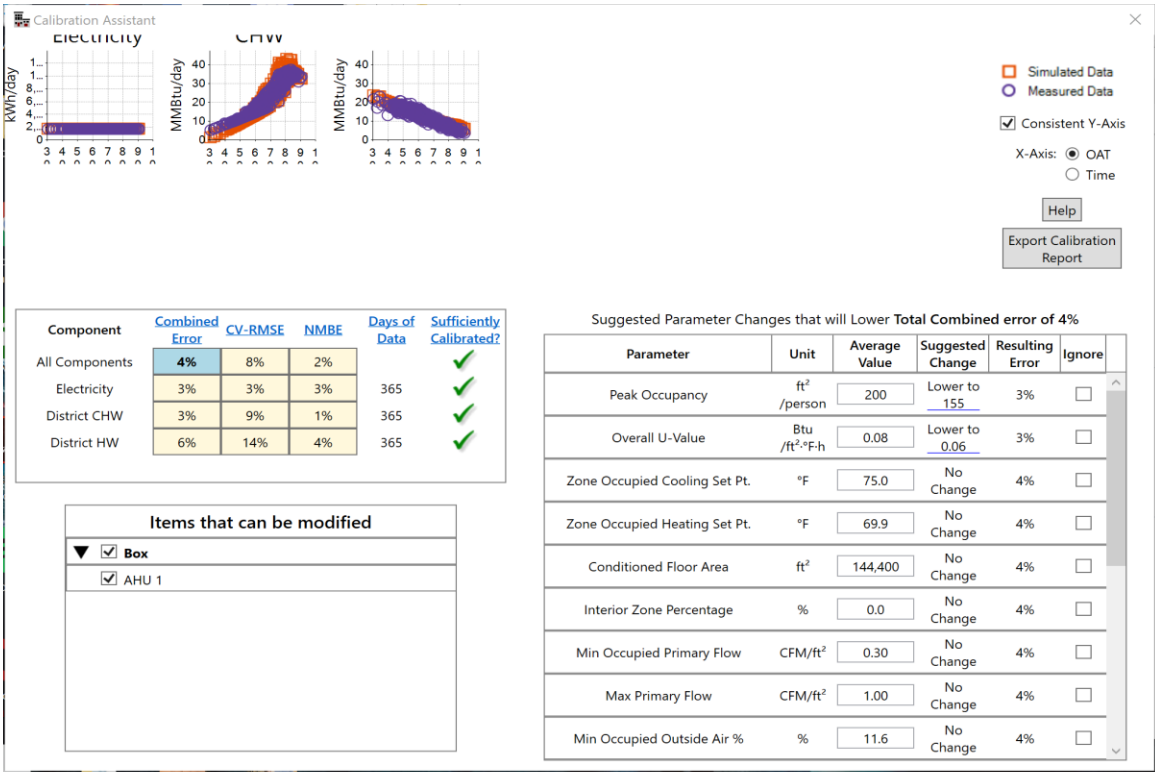

Figure 37: Final calibration report in WinAM

Figure 37 shows the final calibration page of WinAM. The total and combined error is now 4% and is a value that WinAM considers properly calibrated.

CHAPTER V

WINAM UNOCCUPIED MODE

This next section covers a brief detour taken during the research that led to an important update in WinAM. After the thermal mass effects were observed, the next step was to examine thermal mass effects with a setback. A WinAM model was created similar to the one listed in Table 3, with the addition of a temperature setback during unoccupied hours. The model is occupied from 7AM to 6PM and used the following temperature setback:

- Unoccupied Cooling Zone Setpoint: 85^{o}F
- Occupied Cooling Zone Setpoint: 75^{o}F
- Occupied Heating Zone Setpoint: 72^{o}F
- Unoccupied Heating Zone Setpoint: 62^{o}F

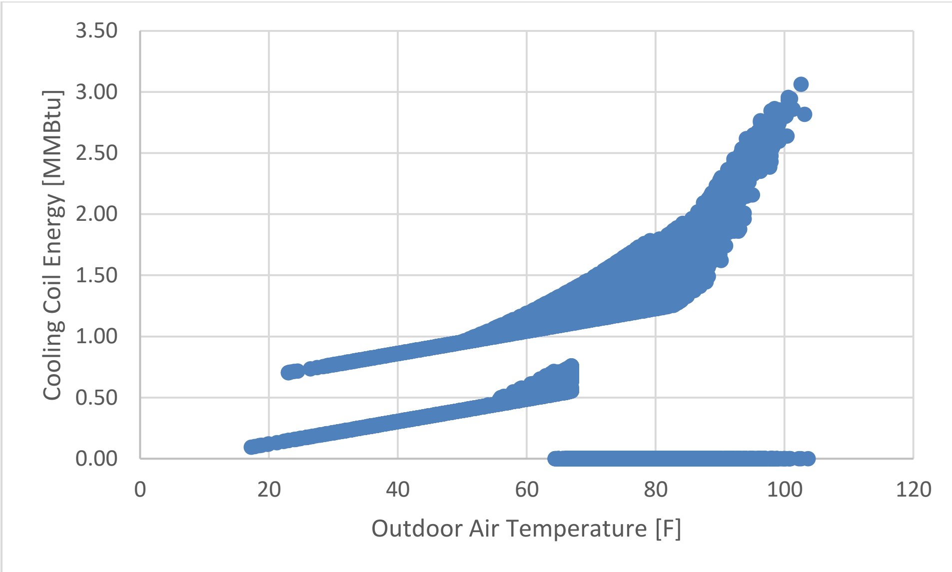

Figure 38: WinAM cooling coil energy with setback

Figure 38 shows zero cooling at temperatures above 62°F, which is unusual because most systems would require cooling at warm temperatures. The zeroes were filtered out and occur at times that do not show a specific pattern. This file and graph were sent to Kevin Christman who was able to determine the bug causing the problem. He says, "This bug is caused because we are turning off the fan when the space is in unoccupied mode under certain conditions. Today, I confirmed with Carlos Yagua (an ESL CC engineer) that this behavior is not how real systems work." WinAM has since been updated with the bug fixed and the cooling coil energy behaving as expected. With this issue resolved, thermal mass and setback effects can be investigated.

CHAPTER VI

TEMPERATURE SETBACK

This section covers the effects of thermal mass and temperature setback on the heating and cooling consumption of a simple building in three different climates. College Station represents a warm climate, Chicago represents a cold climate, and San Francisco represents a temperate climate. Table 5 shows the important design parameters of the building. There is a total of 18 EnergyPlus simulations which are broken up in the following order for the three climates:

- Simulation 1: Massless construction no temperature setback
- Simulation 2: Massless construction, temperature setback
- Simulation 3: Light mass construction, no temperature setback
- Simulation 4: Light mass construction, temperature setback
- Simulation 5: Heavy mass construction, no temperature setback
- Simulation 6: Heavy mass construction, temperature setback

There are also two WinAM simulations for each climate that are compared to the EnergyPlus models. Since WinAM does not account for thermal mass, the two simulations for the three climates are the following:

- WinAM 1-3-5: Massless construction, no temperature setback
- WinAM 2-4-6: Massless construction, temperature setback

As the name indicates, WinAM 1-3-5 is compared to EnergyPlus Simulations 1, 3, and 5, while WinAM 2-4-6 is compared to EnergyPlus Simulations 2, 4, and 6.

Each EnergyPlus model was then used as daily metered consumption for WinAM calibration. A calibration report was created for all 18 simulations to see what changes WinAM would make to calibrate itself with EnergyPlus. These results are discussed in the last section of each climate.

Table 5: Important parameters and values

Description	Value
Building Area [ft^2]	100,000
Number of zones	1
Floor to floor height [ft]	12
Window area [%]	15
T_{CL} [°F]	55
Wall/roof thermal conductance [Btu/hr-ft^2-°F]	0.089
Window thermal conductance [Btu/hr-ft^2-°F]	0.48
Peak occupancy [ft^2/person]	200
Peak Lighting load [W/ft^2]	1.13
System type	Single duct VAV
Design flow rate [CFM/ft^2]	1
Minimum flow [%]	30
Outside air [CFM/ft^2]	0.085
Unoccupied cooling setpoint [°F]	85
Occupied cooling setpoint [°F]	75
Occupied heating setpoint [°F]	72
Unoccupied heating setpoint [°F]	62
Overall Wall Thermal Absorptance	0.9
Solar Absorptance	0.7
Occupied Hours	7:00 AM- 6:00PM
Inside Convection Coefficient [Btu/hr-ft^2-°F]	1.46
Outside Convection Coefficient [Btu/hr-ft^2-°F]	4
Supply fan total pressure [inWG]	2
Static pressure set point [inWG]	1.4

Table 5 is a list of the most important parameters used in the simulations. Thermal absorptance, solar absorptance, inside convection coefficient, and outside coefficient were inputs for EnergyPlus only. However, the inside and outside convection coefficients were considered when computing the total wall resistance value input for WinAM. Because of this, the total wall resistance values match for EnergyPlus and WinAM. The values for the convection coefficients were determined from the ASHRAE fundamentals handbook (ASHRAE Handbook: Fundamentals, 1999).

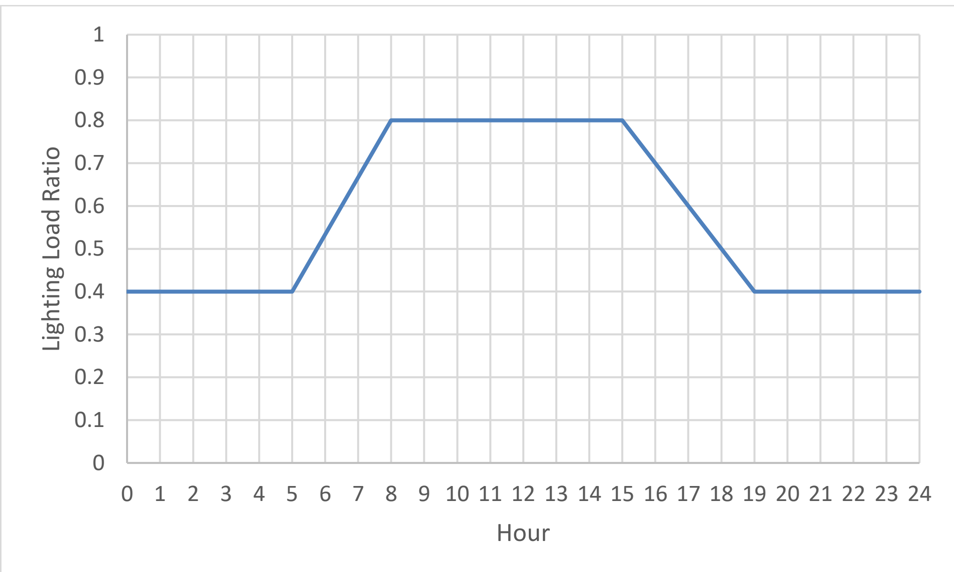

Figure 39: Lighting load ratio schedule

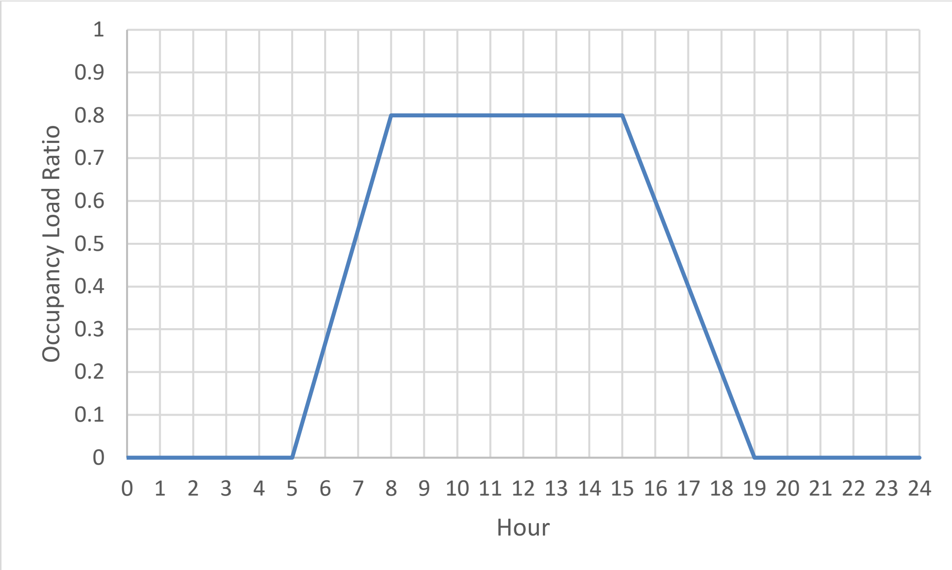

Figure 40: Occupancy load ratio schedule

Figures 39 and 40 show the lighting load ratio and occupancy load ratio, respectively. The lighting load ratio is based on a medium sized office building from *Electricity Diversity Profiles for Energy Simulation of Office Buildings* (Claridge, et al., 2004). The occupancy load ratio is made to match the lighting load except the ratio goes to zero at night since it is typically assumed some lights remain on while all occupants leave in the evening.

Table 6: Layers for light mass wall construction

Light Mass Wall				
	25mm Wood	50mm Insulation	19mm Gypsum	Total
Thickness [m]	0.025	0.051	0.019	---
Conductivity [W/m-K]	0.15	0.03	0.16	---
Density [kg/m^3]	608	43	800	---
Specific heat [J/kg-K]	1630	1210	1090	---
Resistance [m^2-K/W]	0.169	1.693	0.119	**1.981**

Table 7: Layers for heavy mass wall construction

Heavy Mass Wall					
	4” Brick	25mm Wood	47mm Insulation	19mm Gypsum	Total
Thickness [m]	0.1016	0.025	0.047	0.019	---
Conductivity [W/m-K]	0.9	0.15	0.03	0.16	---
Density [kg/m^3]	1920	608	43	800	---
Specific heat [J/kg-K]	790	1630	1210	1090	---
Resistance [m^2-K/W]	0.113	0.169	1.58	0.119	**1.981**

Tables 6 and 7 show the wall construction for the light mass and heavy mass wall. The massless wall has the same resistance value with a thermal absorptance of 0.9 and a solar absorptance of 0.7. All layers of the wall construction have the same thermal and solar absorptance values as the massless construction. The light mass and heavy mass walls have similar construction, with a brick layer added to the outside for the heavy mass wall. This brick layer was added to increase the thermal mass of the wall construction due to brick’s high density. Because of the addition of the brick layer, the heavy mass wall has a slightly thinner insulation layer to keep the overall resistance constant for all constructions. The massless case also has a massless floor, while all other constructions have a half inch concrete floor. This value was chosen arbitrarily because previous tests showed little change in consumption as floor thickness was increased. The previous tests considered a 5-story building with 9 inch, and 12 inch concrete floor thickness. Some input parameters are different than the model listed above, but the main purpose was to compare the cooling and heating consumption with varying floor thickness.

Table 8: Annual consumption for 5 story building with varying floor thickness

	Heating [MMBtu]	Cooling [MMBtu]
9 inches	606.62	3777.73
12 inches	571.53	3714.41

Table 8 shows the annual cooling and heating consumption for each of the cases. The percent difference between the 9 inch case and the 12 inch case is 5.95% for heating and 1.69% for cooling. Since these values are small, it can be assumed the floor thickness has little effect on the consumption of the one-story building being simulated in this section. However, future work should include varying floor constructions to ensure all possible effects are being accounted for.

VI.I College Station

The first climate observed is College Station. College Station represents a warm, humid climate.

VI.I.I Simulation 1

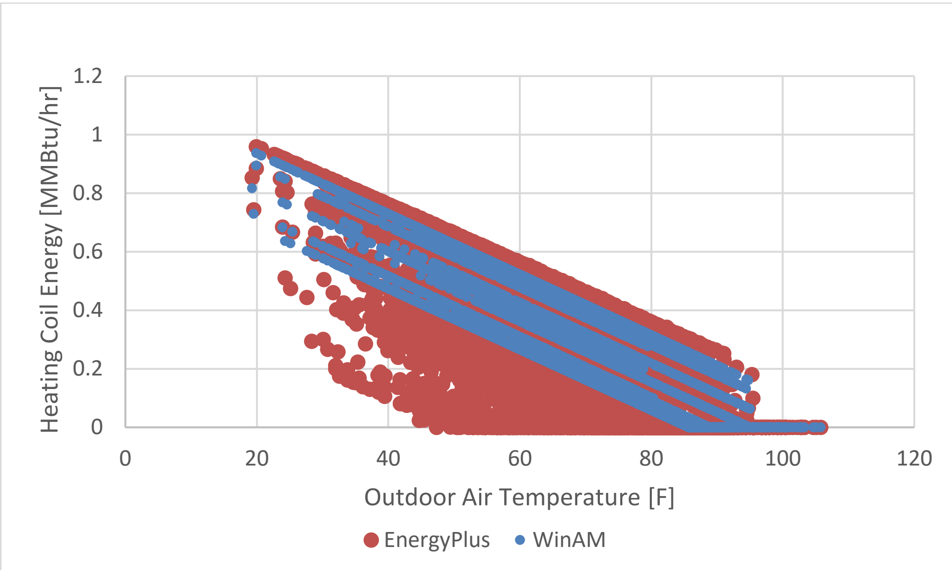

Figure 41: Hourly heating coil energy consumption for a massless construction without temperature setback

Figure 41 shows the hourly heating coil energy output of EnergyPlus and WinAM for a massless construction. The annual heating consumption for EnergyPlus is 2,675 MMBtu and the annual heating consumption for WinAM is 2,940 MMBtu. It shows EnergyPlus predicting significantly more spread in the hourly cooling than WinAM. This is due to the thermal absorptance and mass of the wall. When the thermal absorptance is set to zero, there is no spread in the EnergyPlus heating coil energy because all transient effects are virtually "turned off." This is similar to the computing process of WinAM; the simulation does not account for the previous hour, but rather computes the heating coil energy one hour at a time. When thermal absorptance is set to the default value of 0.9 in EnergyPlus, the spread is seen. Thermal absorptance is described as "the fraction of incident long wavelength infrared radiation that is absorbed by the material" (LLC, Big Ladder Software, 2018). The explanation of this spread will be discussed in section 6.1.7.

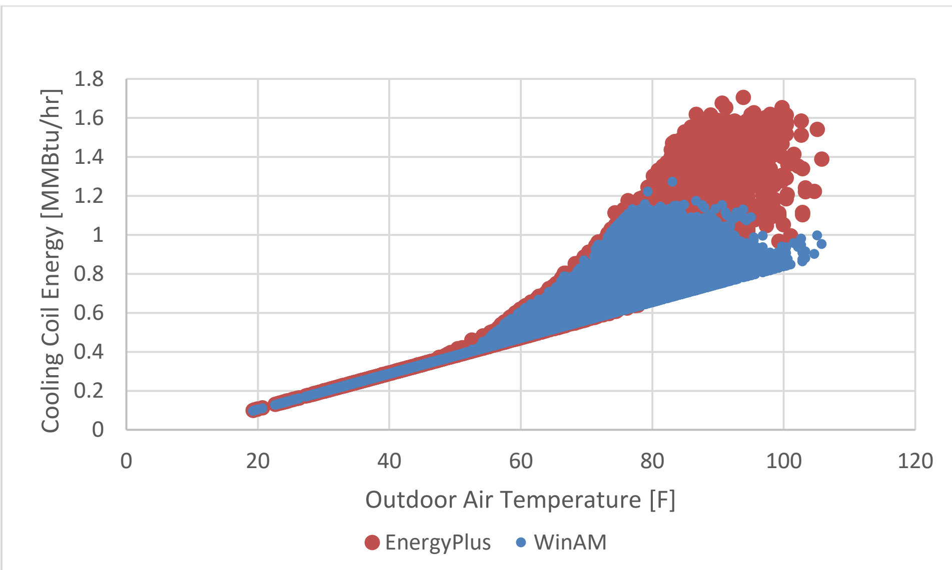

Figure 42: Hourly cooling coil energy consumption for a massless construction without temperature setback

Figure 42 represents the cooling coil energy consumption of EnergyPlus and WinAM for a massless construction with no setback. The annual cooling consumption for EnergyPlus is 6,605 MMBtu and the annual cooling consumption for WinAM is 5,690 MMBtu. Like the heating, there is more spread in the EnergyPlus model because of the thermal and solar absorptance. The lack of thermal and solar absorptance effects leads to an underprediction in cooling coil energy by WinAM.

The calibration for Simulation 1 recommended the following:

- Increasing peak occupancy from 200 ft^2/person to 50 ft^2/person
- Increasing heating zone setpoint from 72°F to 73.4°F

After these changes were made, the WinAM total component error was at 40%, a value low enough to consider the model calibrated.

VI.I.II Simulation 2

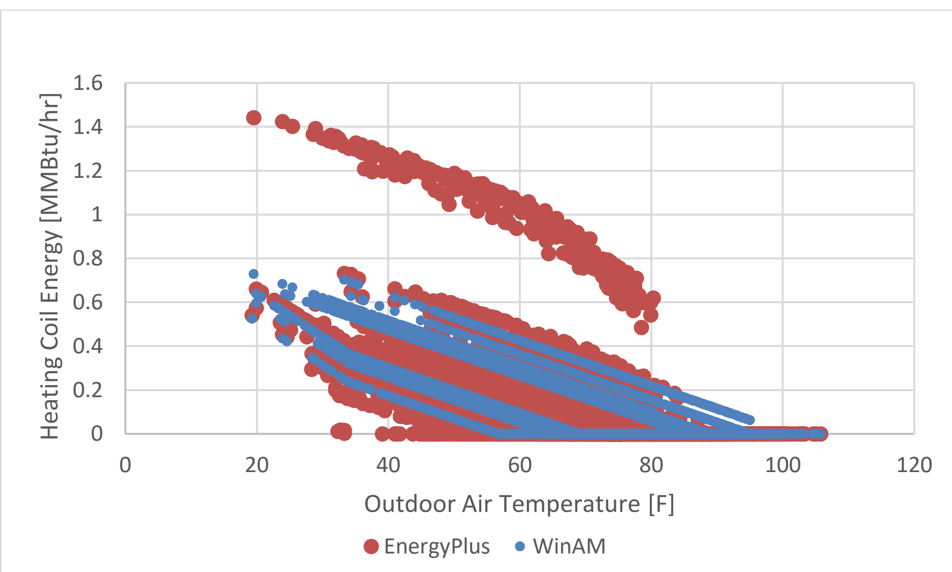

Figure 43: Hourly heating coil energy consumption for a massless construction with temperature setback

Figure 43 represents the heating coil energy consumption of EnergyPlus and WinAM for a massless construction with a temperature setback. The annual heating consumption for EnergyPlus is 1,035 MMBtu and the annual heating consumption for WinAM is 1,140 MMBtu. Again, there is more spread in the EnergyPlus output due to thermal and solar absorption. Another difference is the high heating values from 20°F to 80°F. All of these points occur at 7AM when the system switches from unoccupied to occupied mode. EnergyPlus reveals that at each of these points, the heating temperature setpoint is not being met in the zone. Because some energy is stored in the walls, the zone takes longer to warm up from 62°F to 72°F. The system combats this by increasing the flowrate at 7AM, trying to meet the load requirement. The increase in flowrate leads to an increase in the heating coil energy.

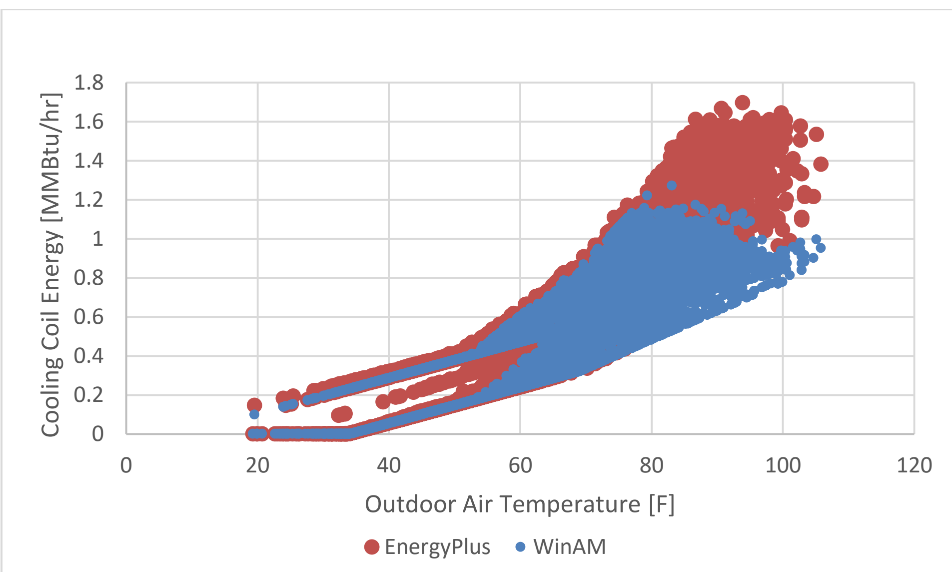

Figure 44: Hourly cooling coil energy consumption for a massless construction with temperature setback

Figure 44 represents the cooling coil energy consumption of EnergyPlus and WinAM for a massless construction with a temperature setback. The annual cooling consumption for EnergyPlus is 5,665 MMBtu and the annual cooling consumption for WinAM is 4,715 MMBtu. Similar to the figure above, the cooling coil energy output of EnergyPlus reveals two extra "tails" from 30^{o}F to 60^{o}F. The points of middle tail between the two WinAM tails all occur at 6PM when the system switches from occupied mode to unoccupied mode. The points of the upper most tail all occur at 7AM when the system switches from unoccupied to occupied mode.

The calibration for Simulation 2 recommended the following:

- Increasing unoccupied outdoor air from 8.5% to 17.6%
- Increasing peak occupancy from 200 ft^{2}/person to 97 ft^{2}/person
- Increasing heating zone setpoint from 72^{o}F to 72.6^{o}F

After these changes were made, the WinAM total component error was at 40%, a value too high for WinAM to consider the model calibrated.

VI.I.III Simulation 3

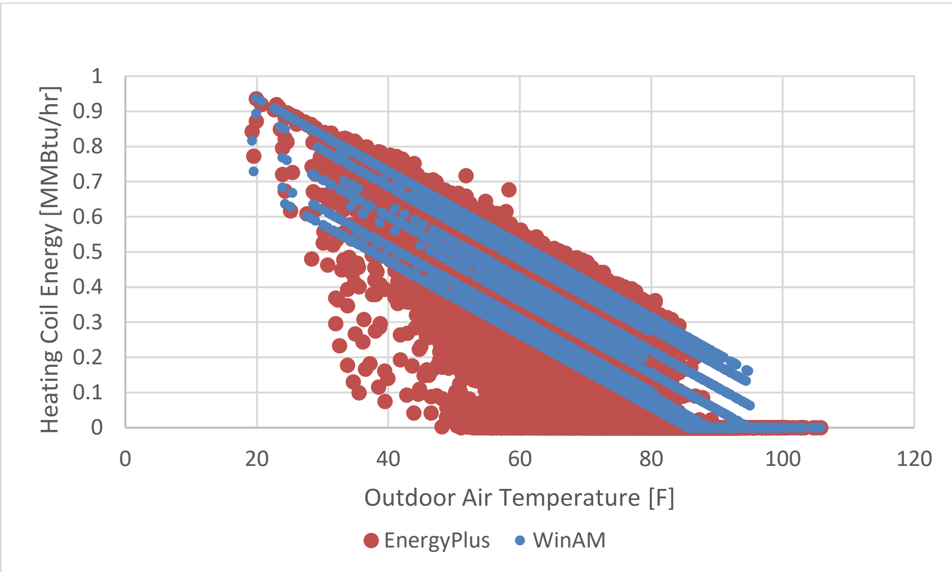

Figure 45: Hourly heating coil energy consumption for a light mass construction without temperature setback

Figure 45 represents the heating coil energy consumption of EnergyPlus and WinAM for a light mass construction without a temperature setback. The annual heating consumption for EnergyPlus is 2,445 MMBtu and the annual heating consumption for WinAM is 2,940 MMBtu. This figure shows slightly less spread in the EnergyPlus heating than Figure 47, a trend that will be discussed later in the section. The WinAM heating stays the same as run 1 because it does not account for thermal mass changes.

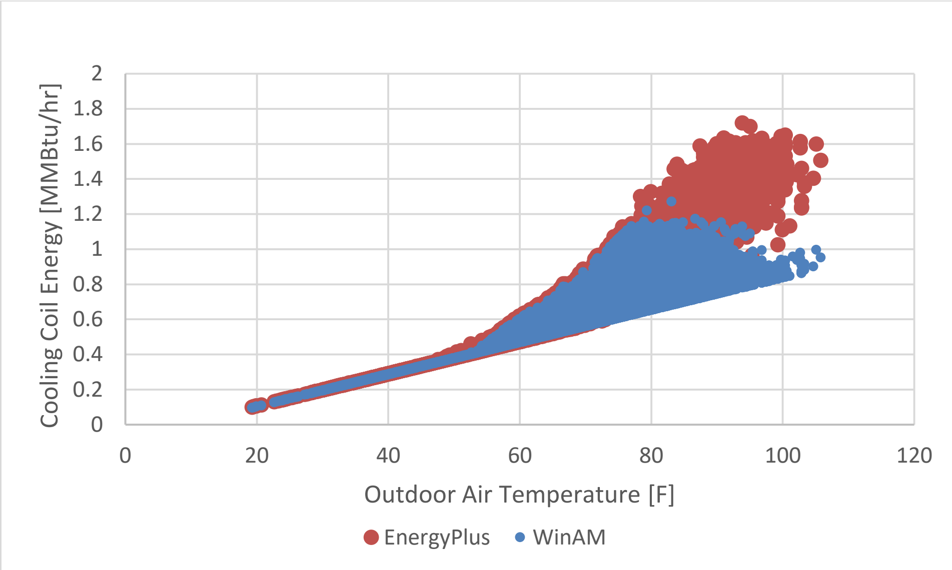

Figure 46: Hourly cooling coil energy consumption for a light mass construction without temperature setback

Figure 46 represents the cooling coil energy consumption of EnergyPlus and WinAM for a light mass construction without a temperature setback. The annual cooling consumption for EnergyPlus is 6,525 MMBtu and the annual cooling consumption for WinAM is 5,690 MMBtu. Like the heating, this figure shows less spread in the EnergyPlus cooling than the massless construction.

The calibration for Simulation 3 recommended the following:

- Increasing peak occupancy from 200 ft^2/person to 50 ft^2/person
- Increasing heating zone setpoint from 72^oF to 72.6^oF
- Decreasing static pressure setpoint from 1.4 inWG to 1.25 inWG

After these changes were made, the WinAM total component error was at 14%, a value low enough to consider the model calibrated.

VI.I.IV Simulation 4

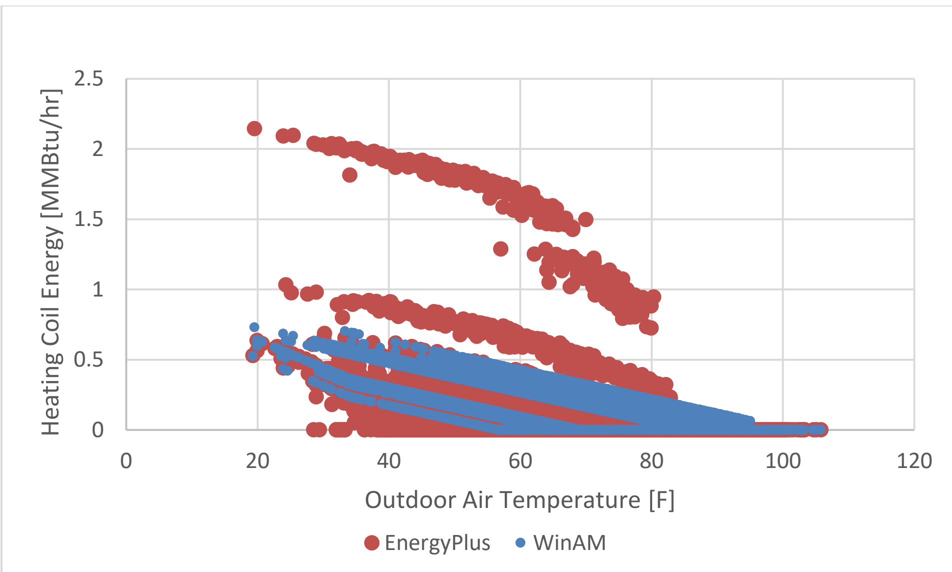

Figure 47: Hourly heating coil energy consumption for a light mass construction with temperature setback

Figure 47 represents the heating coil energy consumption of EnergyPlus and WinAM for a light mass construction with a temperature setback. The annual heating consumption for EnergyPlus is 1,215 MMBtu and the annual heating consumption for WinAM is 1,140 MMBtu.

Similar to previous runs, this figure shows high heating when the system switches from unoccupied to occupied mode.

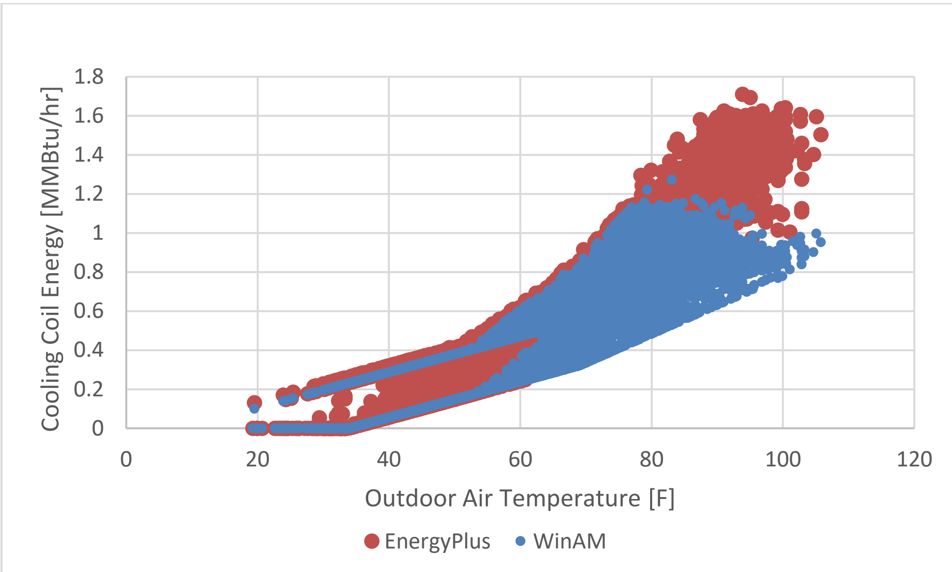

Figure 48: Hourly cooling coil energy consumption for a light mass construction with temperature setback

Figure 48 represents the cooling coil energy consumption of EnergyPlus and WinAM for a light mass construction with a temperature setback. The annual cooling consumption for EnergyPlus is 5,860 MMBtu and the annual cooling consumption for WinAM is 4,715 MMBtu. This figure also shows extra “tails” due to increased flowrate when the system switches between occupied and unoccupied modes.

The calibration for Simulation 4 recommended the following:

- Increasing minimum unoccupied outdoor air from 8.5% to 22.4%
- Decreasing unoccupied heating zone setpoint from 62°F to 60.6°F

After these changes were made, the WinAM total component error was at 54%, a value too high for WinAM to consider the model calibrated.

VI.I.V Simulation 5

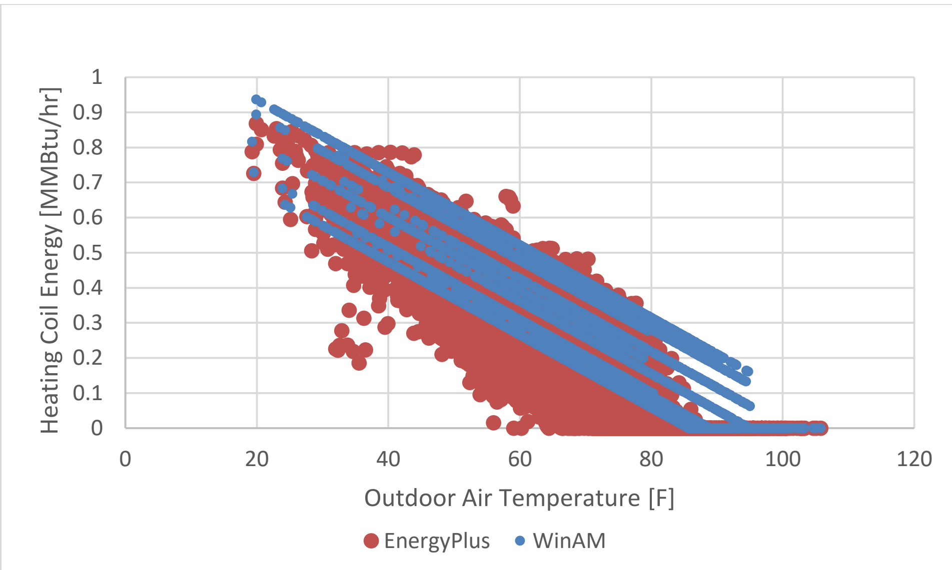

Figure 49: Hourly heating coil energy consumption for a heavy mass construction without temperature setback

Figure 49 represents the heating coil energy consumption of EnergyPlus and WinAM for a heavy mass construction without a temperature setback. The annual heating consumption for EnergyPlus is 2,200 MMBtu and the annual heating consumption for WinAM is 2,940 MMBtu.

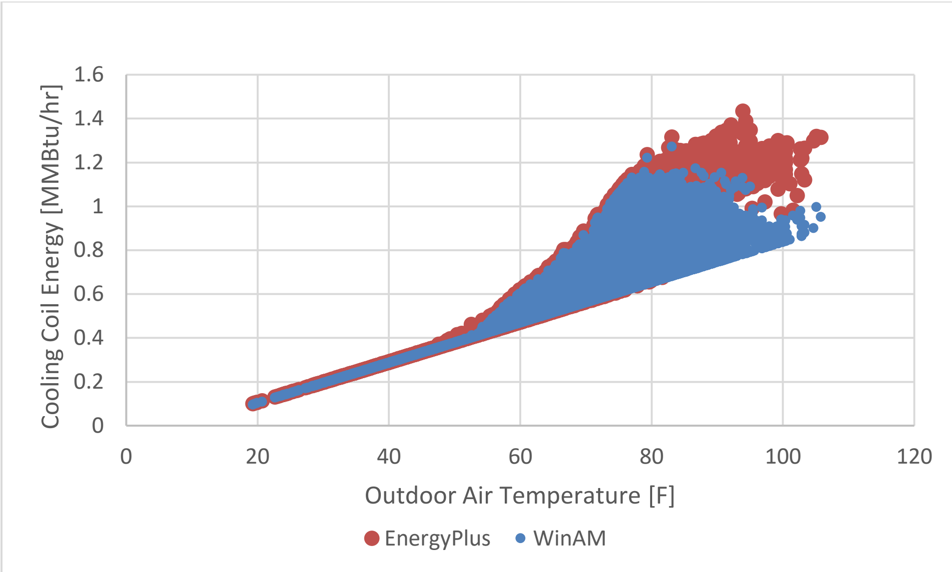

Figure 50: Hourly cooling coil energy consumption for a heavy mass construction without temperature setback

Figure 50 represents the cooling coil energy consumption of EnergyPlus and WinAM for a heavy mass construction without a temperature setback. The annual cooling consumption for EnergyPlus is 6,345 MMBtu and the annual heating consumption for WinAM is 5,690 MMBtu.

The calibration for Simulation 5 recommended the following:

- Increasing peak occupancy from 200 ft^2/person to 50 ft^2/person
- Decreasing minimum unoccupied flow rate from 0.3 CFM/ft^2 to 0.29 CFM/ft^2

After these changes were made, the WinAM total component error was at 24%, a value too high for WinAM to consider the model calibrated.

VI.I.VI Simulation 6

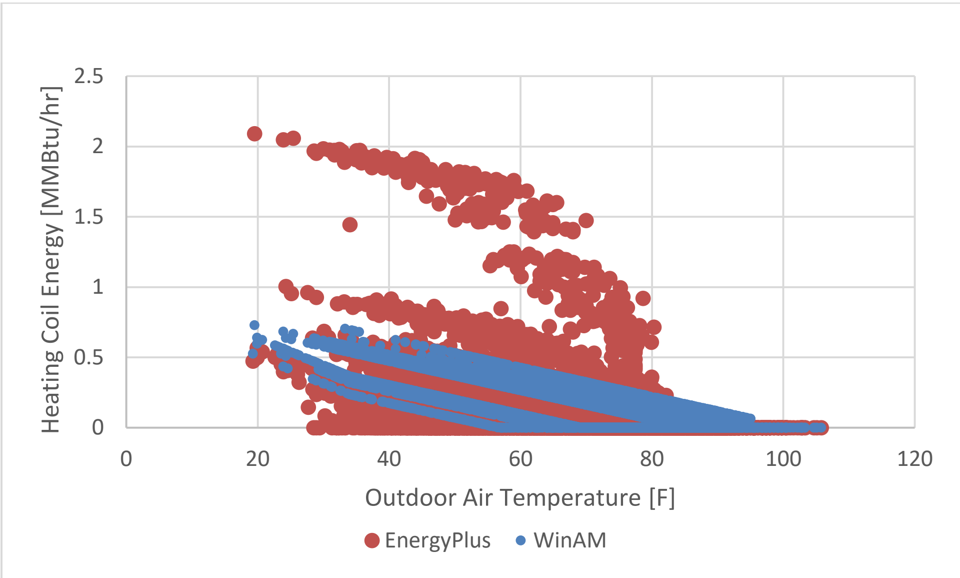

Figure 51: Hourly heating coil energy consumption for a heavy mass construction with temperature setback

Figure 51 represents the heating coil energy consumption of EnergyPlus and WinAM for a heavy mass construction with a temperature setback. The annual heating consumption for EnergyPlus is 1,195 MMBtu and the annual heating consumption for WinAM is 1,140 MMBtu.

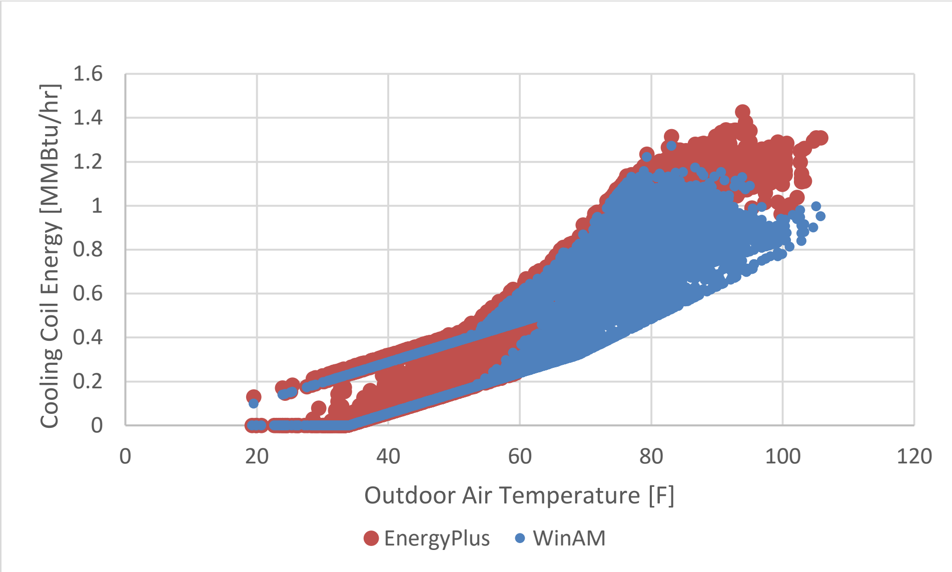

Figure 52: Hourly cooling coil energy consumption for a heavy mass construction with temperature setback

Figure 52 represents the cooling coil energy consumption of EnergyPlus and WinAM for a heavy mass construction with a temperature setback. The annual cooling consumption for EnergyPlus is 5,800 MMBtu and the annual cooling consumption for WinAM is 4,715 MMBtu.

The calibration for Simulation 3 recommended the following:

- Increasing minimum unoccupied outdoor air from 8.5% to 22.4%
- Decreasing wall U-value from 0.09 Btu/hr-ft^2-^{o}F to 0.05 Btu/hr-ft^2-^{o}F

After these changes were made, the WinAM total component error was at 36%, a value too high for WinAM to consider the model calibrated.

VI.I.VII Results Comparison and Analysis

Figures 41 through 52 show that WinAM is over-predicting heating in most cases and under-predicting the amount of spread. Figures 47 through 58 show that higher mass constructions lead to a better match in cooling. EnergyPlus results show that lower mass constructions have more spread than higher mass constructions. Default values used in EnergyPlus; 0.9 for thermal absorptance and 0.7 for solar absorptance. EnergyPlus manual describes the inputs as the following: "The thermal absorptance…represents the fraction of incident long wavelength radiation that is absorbed by the material… 1.0 represents 'black body' conditions," and "The solar absorptance field…represents the fraction of incident solar radiation that is absorbed by the material" (pg. 101). Because of the relatively high absorptance values, most of the energy due to the temperature and solar radiation are absorbed into the building material. A high mass construction would store this energy while a low mass construction would easily transfer it to the space. This is what causes the large spread in the massless and low mass constructions; the energy is not stored well in the walls and transfers into the space leading to greater variation and a poor match with WinAM that does not include solar absorptance.

All figures from the simulations with a setback show high heating and extra cooling "tails." As mentioned in Figures 43 and 44, these points occur during 7AM when the building becomes occupied, and 6PM when the building becomes unoccupied. The system increases flowrate to help meet the new zone temperature setpoint, leading to a direct increase in both heating and cooling.

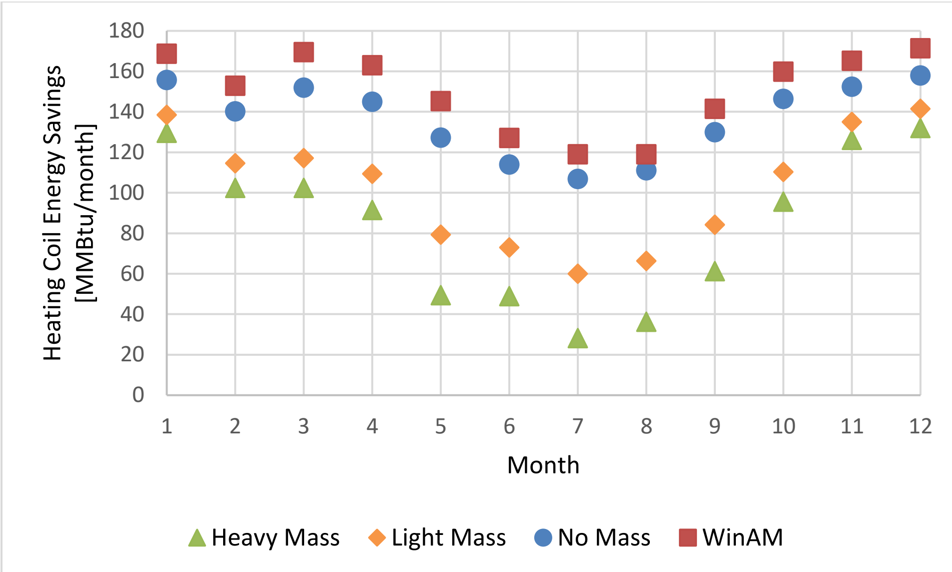

Figure 53: Monthly heating coil energy savings due to temperature setback

Figure 53 represents the monthly heating energy savings predicted when implementing a temperature setback. The figure shows the EnergyPlus No Mass construction and WinAM are close in their savings predictions. However, as more thermal mass is added to the construction, the difference in savings predicted by EnergyPlus diverges from the WinAM prediction. For increased thermal mass, EnergyPlus predicts less monthly savings, especially in summer months. This means that WinAM is over-predicting the amount of energy savings produced by a temperature setback if the building has high thermal mass. The annual heating savings for each construction are the following:

- WinAM: 1,800 MMBtu
- No Mass: 1,640 MMBtu
- Light Mass: 1,230 MMBtu

- Heavy Mass: 1,000 MMBtu

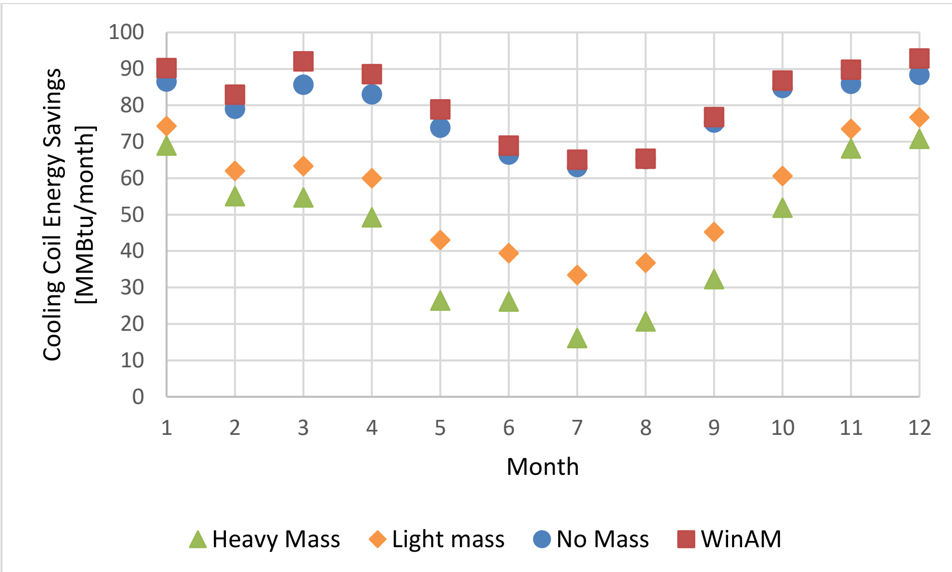

Figure 54: Monthly cooling coil energy savings due to temperature setback

Figure 54 represents the monthly cooling energy savings predicted when implementing a temperature setback. Like the heating, WinAM over-predicts the cooling energy savings for higher mass construction. The annual cooling savings for each construction are the following:

- WinAM: 980 MMBtu
- No Mass: 940 MMBtu
- Light Mass: 670 MMBtu
- Heavy Mass: 540 MMBtu

Higher thermal mass leads to energy being stored in the walls. For a summer day, the temperature setback will enact an 85°F setpoint in the evening when the building is unoccupied to save energy. However, when the building is occupied and the setpoint goes back to 75°F, the system will require more cooling to get the zone to the new setpoint. Higher thermal mass leads to more cooling required during the setback period because of the heat stored in the walls. This increase in cooling required in some cases negates or greatly reduces the energy savings created by the temperature setback. This is the reason WinAM over-predicts cooling and heating and does not accurately simulate the savings created by a temperature setback.

The calibration of WinAM to the EnergyPlus energy consumption is similar for most of the 6 simulations. Four out of six of the simulation calibrations recommended increasing the peak occupancy by four times. Increasing the occupancy is a simple way to increase the internal load of the zone while maintaining the electric load. This increase of internal load within WinAM is a way to raise the heating and cooling requirement to match the higher consumption of EnergyPlus due to the thermal mass effects. Since WinAM does not have a thermal mass input, the calibration process requires a different way to match the EnergyPlus consumption, and one way by increasing the occupancy. Another common method to increase heating to correct for the lack of thermal mass in WinAM is by increasing the heating setpoint. An increase in the zone heating setpoint directly increases the heating load across the reheat coil. Again, since WinAM does not have thermal mass, its heating predicting is lower than the EnergyPlus prediction, thus requiring a different method to calibrate to EnergyPlus. The last common change in the calibration process is an increase in outdoor air flow. This increase leads to the outdoor air temperature having a heavier impact on the cooling and heating since more outdoor air is being used. For warm temperatures, the cooling coil will now require more cooling; for cold temperatures, the cooling coil may require less cooling. This change again seems linked to thermal mass effects. At warm temperatures, heat is stored in the walls leading to more cooling. For cold temperatures, cold is “stored” in the walls, requiring less cooling.

VI.II Chicago

Chicago was chosen to represent a colder climate. The system acts the same as the College Station system, with the addition of a preheat coil. The preheat coil has a setpoint of $40^{o}F$ to ensure the cooling coil does not freeze at low temperatures.

VI.II.I Simulation 1

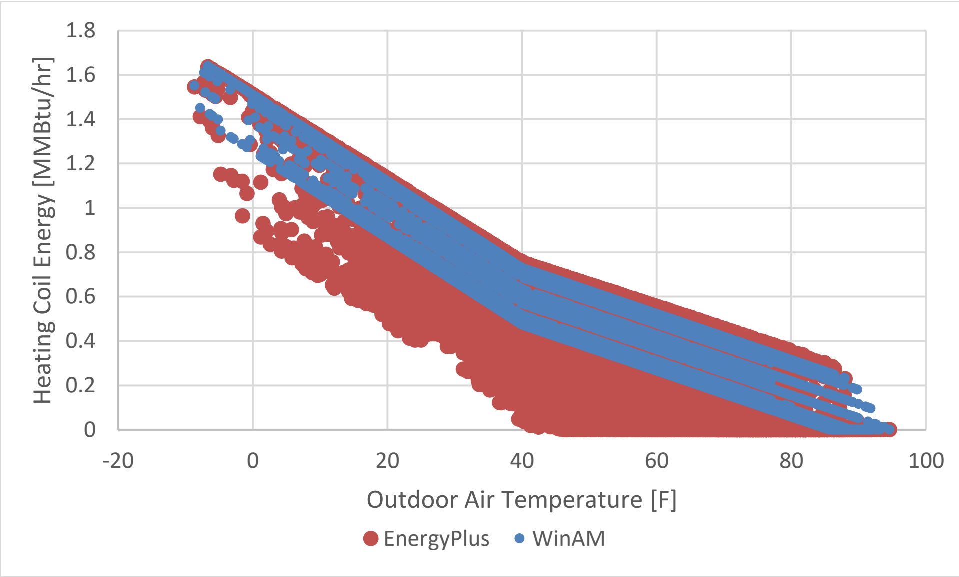

Figure 55: Hourly heating coil energy consumption for a massless construction without temperature setback

Figure 55 represents the heating coil energy consumption of EnergyPlus and WinAM for a massless construction without a temperature setback. The annual heating consumption for EnergyPlus is 4,440 MMBtu and the annual heating consumption for WinAM is 4,880 MMBtu.

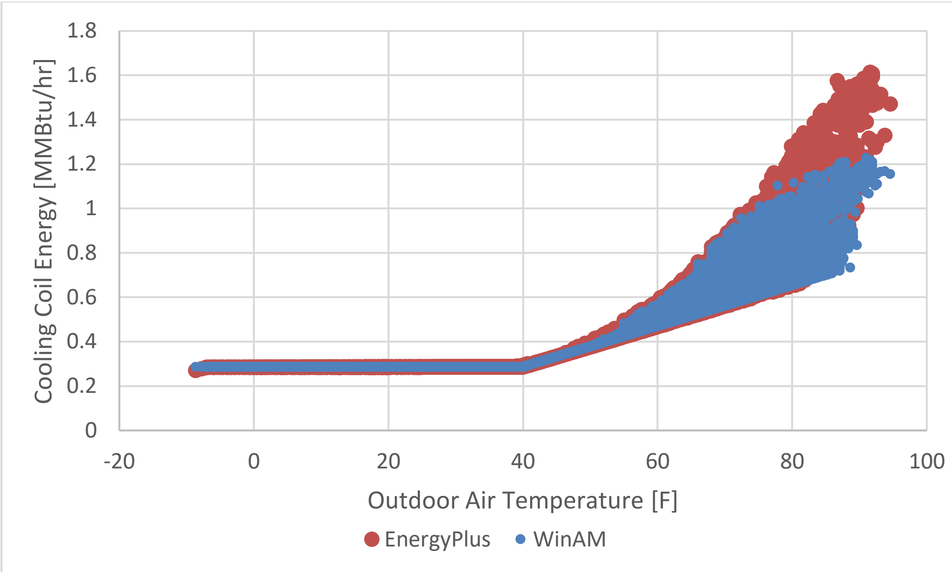

Figure 56: Hourly cooling coil energy consumption for a massless construction without temperature setback

Figure 56 represents the cooling coil energy consumption of EnergyPlus and WinAM for a massless construction without a temperature setback. The annual cooling consumption for EnergyPlus is 4,350 MMBtu and the annual cooling consumption for WinAM is 4,095 MMBtu.

The calibration for Simulation 1 recommended the following:

- Increasing peak occupancy from 200 ft^2/person to 97 ft^2/person
- Increasing peak occupancy from 97 ft^2/person to 81 ft^2/person
- Decreasing cooling coil setpoint from 55^{o}F to 54.8^{o}F

After these changes were made, the WinAM total component error was at 7%, a value low enough to consider the model calibrated.

VI.II.II Simulation 2

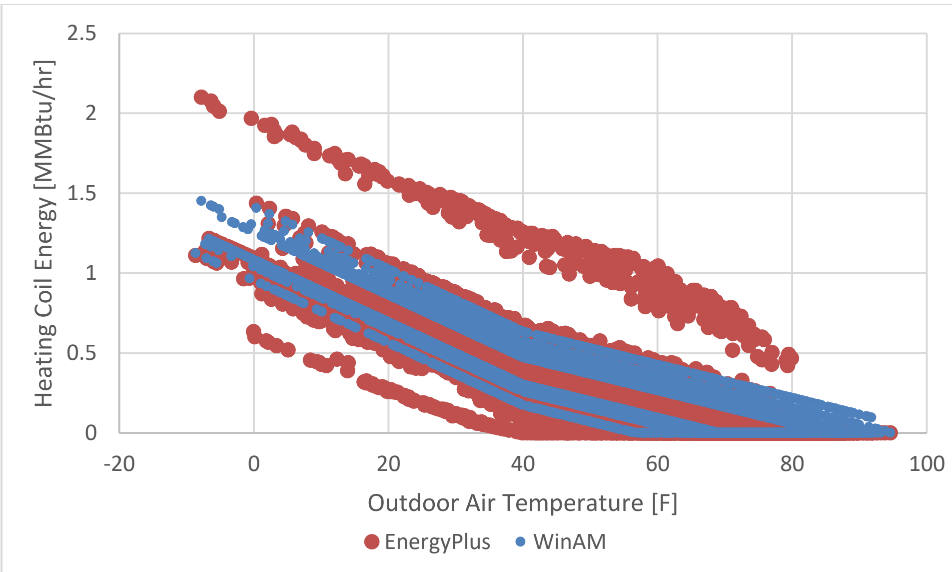

Figure 57: Hourly heating coil energy consumption for a massless construction with temperature setback

Figure 57 represents the heating coil energy consumption of EnergyPlus and WinAM for a massless construction with a temperature setback. The annual heating consumption for EnergyPlus is 2,615 MMBtu and the annual heating consumption for WinAM is 2,910 MMBtu.

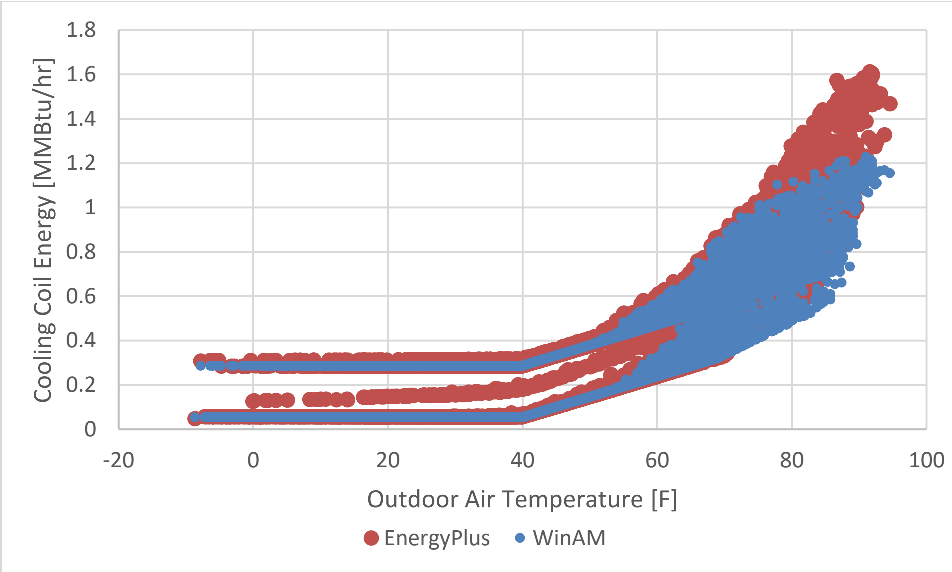

Figure 58: Hourly cooling coil energy consumption for a massless construction with temperature setback

Figure 58 represents the cooling coil energy consumption of EnergyPlus and WinAM for a massless construction with a temperature setback. The annual cooling consumption for EnergyPlus is 3,360 MMBtu and the annual cooling consumption for WinAM is 3,025 MMBtu.

The calibration for Simulation 2 recommended the following:

- Increasing peak occupancy from 200 ft^2/person to 97 ft^2/person
- Decreasing cooling coil setpoint from 55°F to 54.3°F
- Increasing peak occupancy from 97 ft^2/person to 88 ft^2/person
- Decreasing static pressure setpoint from 1.4 inWG to 1.25 inWG

After these changes were made, the WinAM total component error was at 11%, a value low enough to consider the model calibrated.

VI.II.III Simulation 3

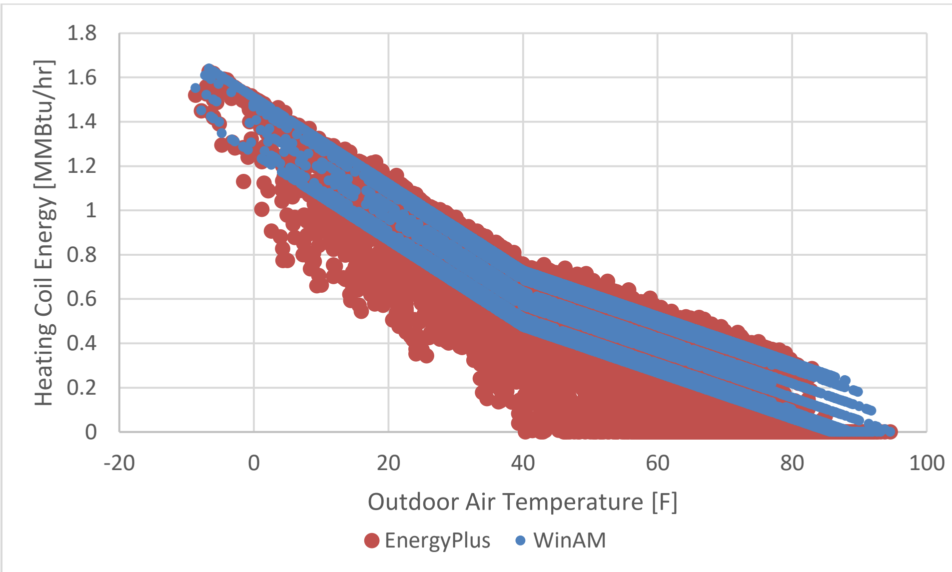

Figure 59: Hourly heating coil energy consumption for a light mass construction without temperature setback

Figure 59 represents the heating coil energy consumption of EnergyPlus and WinAM for a light mass construction without a temperature setback. The annual heating consumption for EnergyPlus is 4,220 MMBtu and the annual heating consumption for WinAM is 4,880 MMBtu.

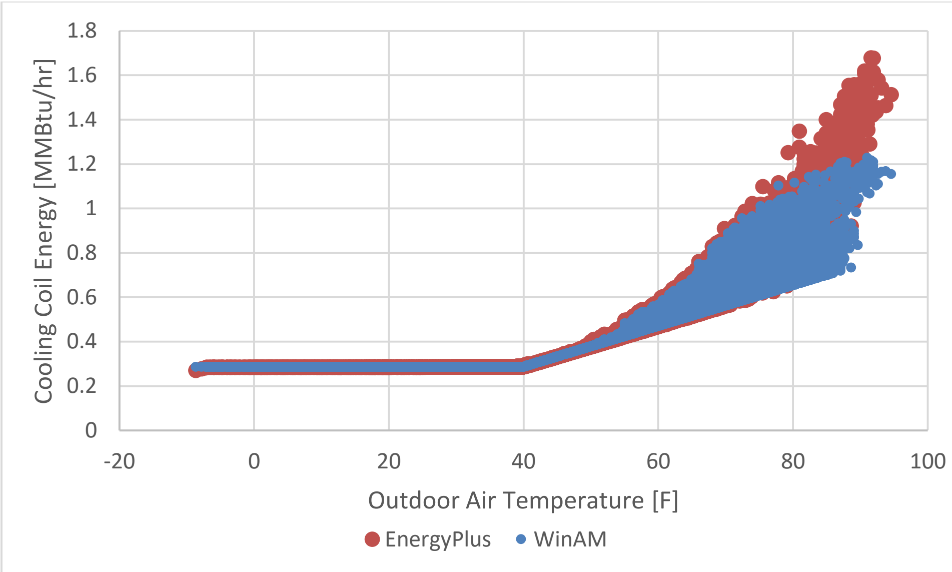

Figure 60: Hourly cooling coil energy consumption for a light mass construction without temperature setback

Figure 60 represents the cooling coil energy consumption of EnergyPlus and WinAM for a light mass construction without a temperature setback. The annual cooling consumption for EnergyPlus is 4,310 MMBtu and the annual cooling consumption for WinAM is 4,095 MMBtu.

The calibration for Simulation 3 recommended the following:

- Increasing peak occupancy from 200 ft^2/person to 97 ft^2/person
- Increasing peak occupancy from 97 ft^2/person to 71 ft^2/person
- Decreasing static pressure setpoint from 1.4 inWG to 1.25 inWG

After these changes were made, the WinAM total component error was at 8%, a value low enough to consider the model calibrated

VI.II.IV Simulation 4

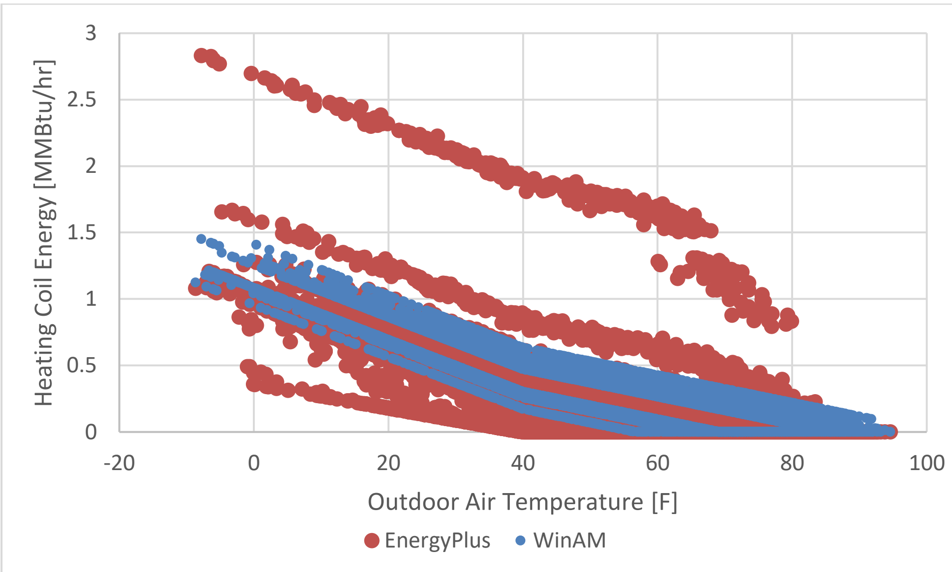

Figure 61: Hourly heating coil energy consumption for a light mass construction with temperature setback

Figure 61 represents the heating coil energy consumption of EnergyPlus and WinAM for a light mass construction with a temperature setback. The annual heating consumption for EnergyPlus is 2,700 MMBtu and the annual heating consumption for WinAM is 2,910 MMBtu.

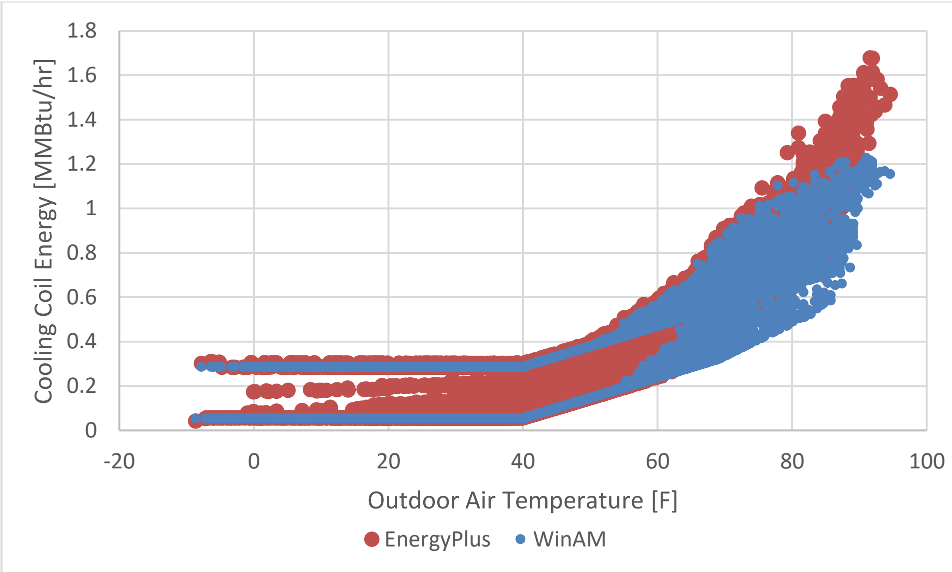

Figure 62: Hourly cooling coil energy consumption for a light mass construction with temperature setback

Figure 62 represents the cooling coil energy consumption of EnergyPlus and WinAM for a light mass construction with a temperature setback. The annual cooling consumption for EnergyPlus is 3,500 MMBtu and the annual cooling consumption for WinAM is 3,025 MMBtu.

The calibration for Simulation 4 recommended the following:

- Decreasing unoccupied heating zone setpoint from 62°F to 61.1°F
- Decreasing cooling coil setpoint from 55°F to 53.8°F
- Increasing peak occupancy from 200 ft^2/person to 172 ft^2/person
- Increasing peak occupancy from 172 ft^2/person to 102 ft^2/person

After these changes were made, the WinAM total component error was at 15%, a value low enough to consider the model calibrated.

VI.II.V Simulation 5

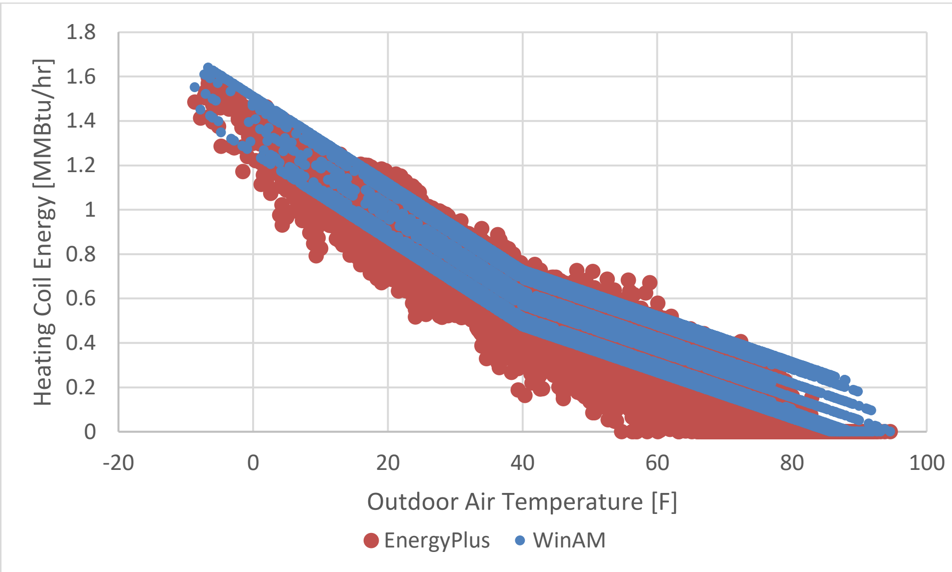

Figure 63: Hourly heating coil energy consumption for a heavy mass construction without temperature setback

Figure 63 represents the heating coil energy consumption of EnergyPlus and WinAM for a heavy mass construction without a temperature setback. The annual heating consumption for EnergyPlus is 4,080 MMBtu and the annual heating consumption for WinAM is 4,880 MMBtu.

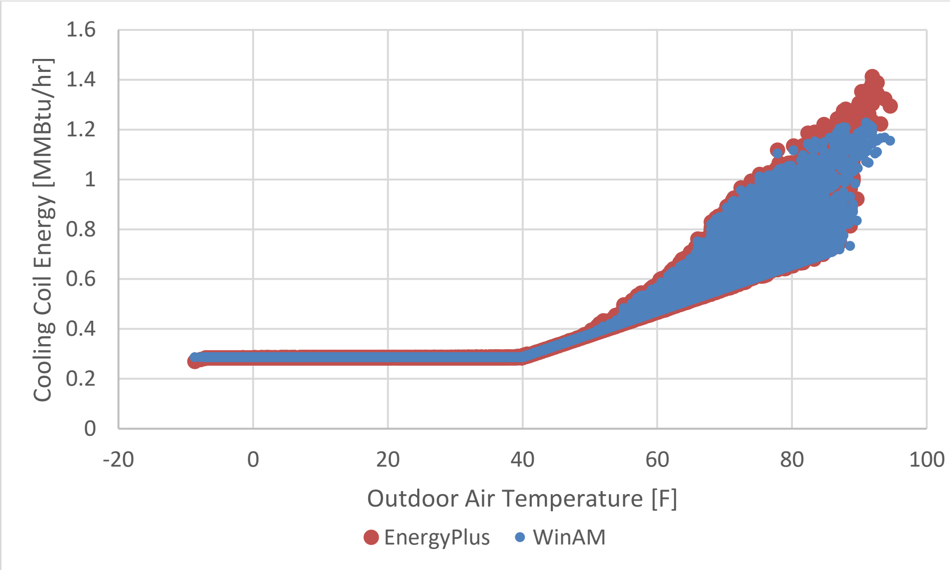

Figure 64: Hourly cooling coil energy consumption for a heavy mass construction without temperature setback

Figure 64 represents the cooling coil energy consumption of EnergyPlus and WinAM for a heavy mass construction without a temperature setback. The annual cooling consumption for EnergyPlus is 4,200 MMBtu and the annual cooling consumption for WinAM is 4,095 MMBtu. The calibration for Simulation 5 recommended the following:

- Increasing peak occupancy from 200 ft^2/person to 97 ft^2/person
- Increasing peak occupancy from 97 ft^2/person to 71 ft^2/person
- Decreasing heating zone setpoint from 72°F to 71.4°F

After these changes were made, the WinAM total component error was at 13%, a value low enough to consider the model calibrated.

VI.II.VI Simulation 6

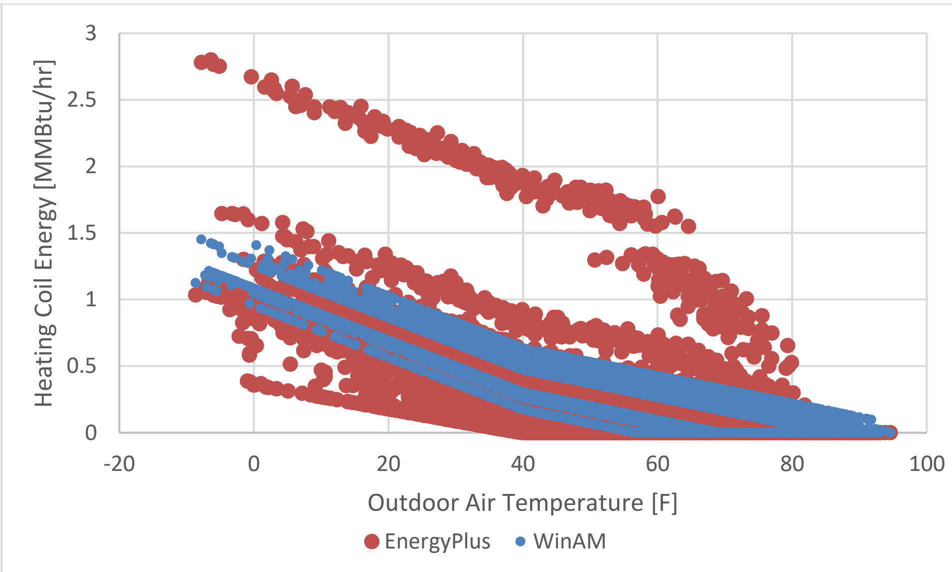

Figure 65: Hourly heating coil energy consumption for a heavy mass construction with temperature setback

Figure 65 represents the heating coil energy consumption of EnergyPlus and WinAM for a heavy mass construction with a temperature setback. The annual heating consumption for EnergyPlus is 2,715 MMBtu and the annual heating consumption for WinAM is 2,910 MMBtu.

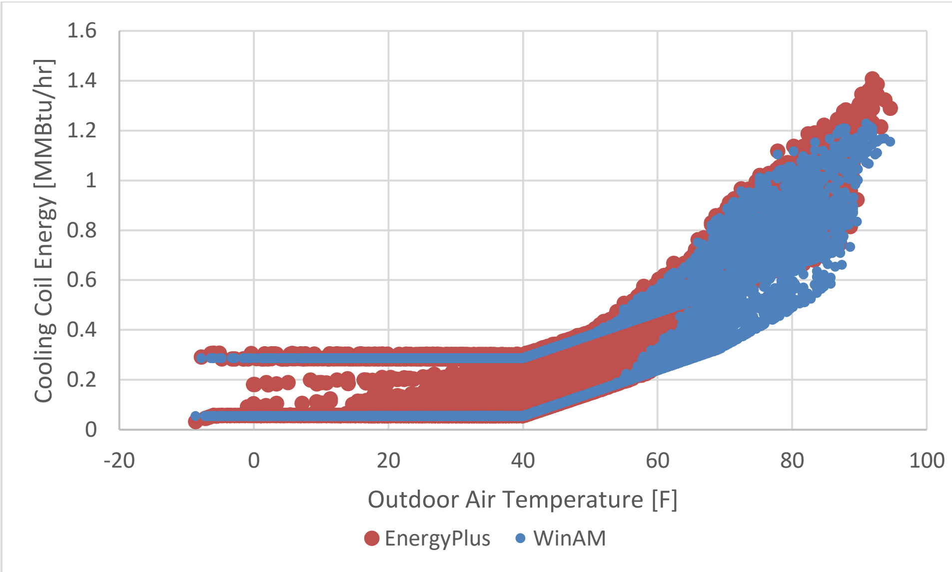

Figure 66: Hourly cooling coil energy consumption for a heavy mass construction with temperature setback

Figure 66 represents the cooling coil energy consumption of EnergyPlus and WinAM for a heavy mass construction with a temperature setback. The annual cooling consumption for EnergyPlus is 3,480 MMBtu and the annual cooling consumption for WinAM is 3,025 MMBtu.

The calibration for Simulation 6 recommended the following:

- Increasing peak occupancy from 200 ft^2/person to 130 ft^2/person
- Decreasing cooling coil setpoint from 55°F to 53.8°F
- Increasing peak occupancy from 130 ft^2/person to 94 ft^2/person
- Decreasing unoccupied heating setpoint from 62°F to 61.4°F

After these changes were made, the WinAM total component error was at 13%, a value low enough to consider the model calibrated.

VI.II.VII Results Comparison and Analysis

All figures from the simulations with a setback show high heating and extra cooling "tails." Similar to College Station, these points occur during 7AM when the building becomes occupied, and 6PM when the building becomes unoccupied. The system increases flowrate to help meet the new zone temperature setpoint, leading to a direct increase in both heating and cooling.

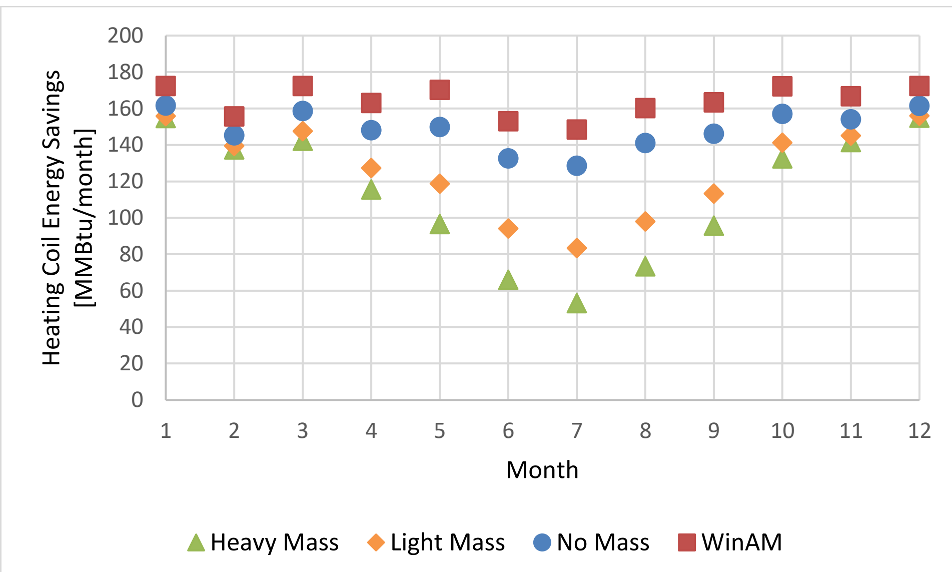

Figure 67: Monthly heating coil energy savings due to temperature setback

Figure 67 represents the monthly heating energy savings predicted when implementing a temperature setback. The annual heating savings for each construction are the following:

- WinAM: 1,970 MMBtu

- No Mass: 1,785 MMBtu
- Light Mass: 1,520 MMBtu
- Heavy Mass: 1,365 MMBtu

Like College Station, the figure shows the EnergyPlus No Mass construction and WinAM close in their savings predictions. This figure shows all construction predicting similar energy savings in the colder months, mostly November through February, but the savings diverging in warmer months. Like College Station results, EnergyPlus predicts lower energy savings than WinAM in the summer months for heavier mass constructions.

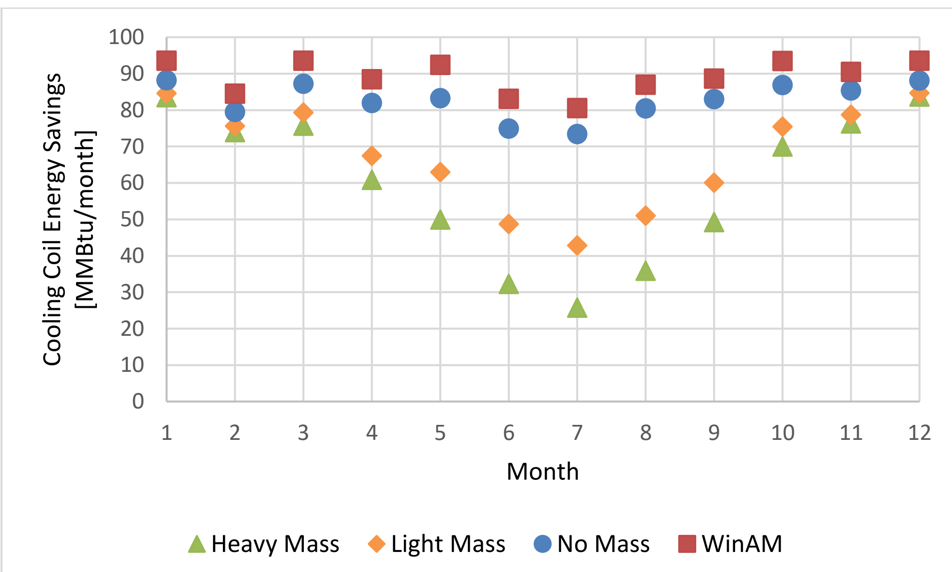

Figure 68: Monthly cooling coil energy savings due to temperature setback

Figure 68 represents the monthly cooling energy savings predicted when implementing a temperature setback. This figure shows a similar trend as the monthly heating energy savings shown in Figure 67. The savings are similar for colder months but diverge in warmer months, with heavier mass constructions predicting lower savings. The annual cooling savings for each construction are the following:

- WinAM: 1,070 MMBtu
- No Mass: 995 MMBtu
- Light Mass: 810 MMBtu
- Heavy Mass: 720 MMBtu

For Chicago, every simulation recommended an increase in peak occupancy by the WinAM calibration. For all cases, the occupancy is more than doubled. As discussed in the College Station results (Section VI.I.VII), this increase in internal load is a simple way to increase the overall heating and cooling consumption of the WinAM model to make up for its lack of thermal mass. Another common recommendation is the lowering of the cooling coil setpoint. A decrease in cooling coil setpoint directly leads to higher cooling consumption, again making up for the lack of thermal mass in WinAM.

VI.III San Jose

San Jose was chosen to represent a temperate climate.

VI.III.I Simulation 1

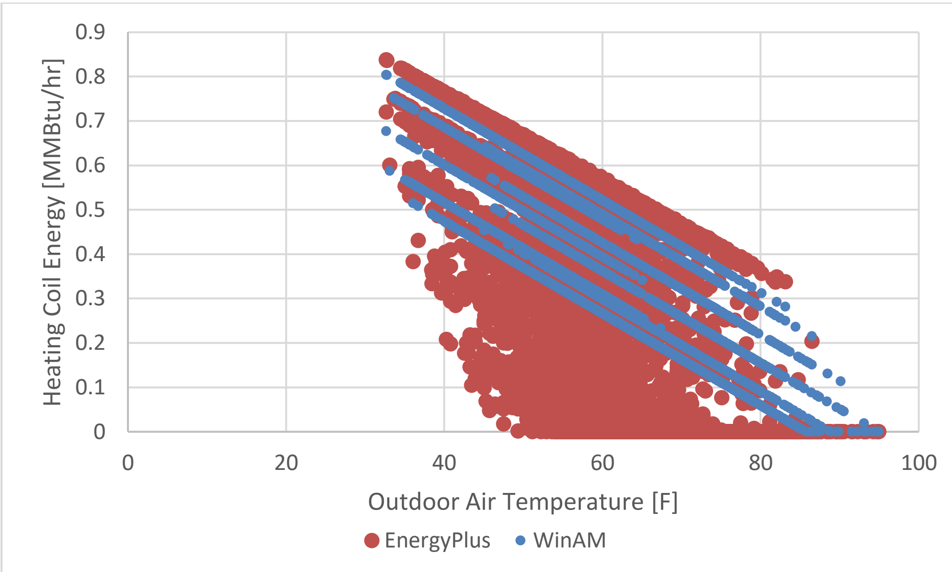

Figure 69: Hourly heating coil energy consumption for a massless construction without temperature setback

Figure 69 represents the heating coil energy consumption of EnergyPlus and WinAM for a massless construction without a temperature setback. The annual heating consumption for EnergyPlus is 3,220 MMBtu and the annual heating consumption for WinAM is 3,700 MMBtu.

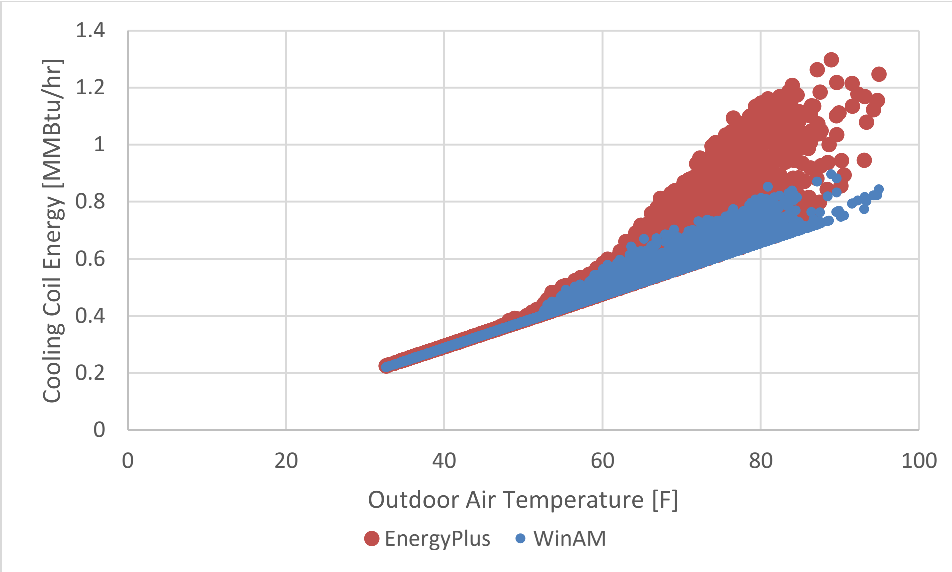

Figure 70: Hourly cooling coil energy consumption for a massless construction without temperature setback

Figure 70 represents the cooling coil energy consumption of EnergyPlus and WinAM for a massless construction without a temperature setback. The annual cooling consumption for EnergyPlus is 4,525 MMBtu and the annual cooling consumption for WinAM is 4,110 MMBtu.

The calibration for Simulation 1 recommended the following:

- Increasing peak occupancy from 200 ft^2/person to 97 ft^2/person
- Increasing peak occupancy from 97 ft^2/person to 88 ft^2/person
- Decreasing minimum unoccupied outdoor air from 8.5% to 5.9%

After these changes were made, the WinAM total component error was at 10%, a value low enough to consider the model calibrated. It should be noted that 5.9% is just below the required unoccupied outdoor air established by ASHRAE 62.1. In a real case, this value should not be changed since the system cannot be operated at this setting. However, it is being used in this simulation strictly for research purposes.

VI.III.II Simulation 2

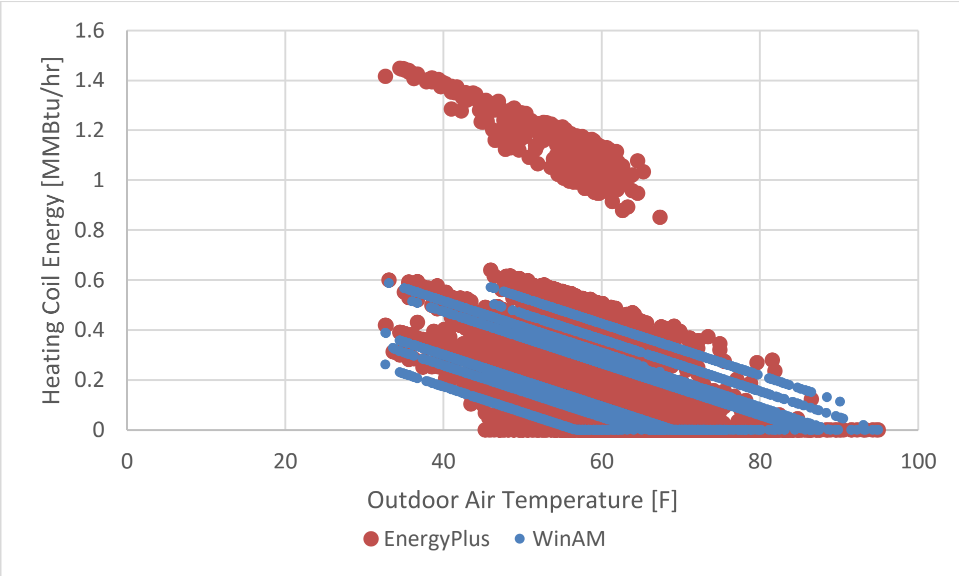

Figure 71: Hourly heating coil energy consumption for a massless construction with temperature setback

Figure 71 represents the heating coil energy consumption of EnergyPlus and WinAM for a massless construction with a temperature setback. The annual heating consumption for EnergyPlus is 1,550 MMBtu and the annual heating consumption for WinAM is 1,685 MMBtu.

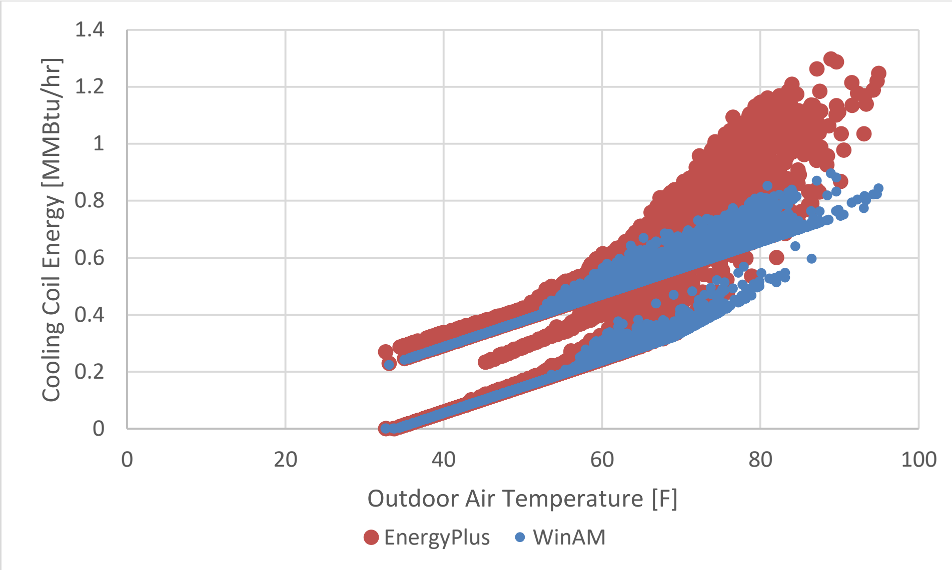

Figure 72: Hourly cooling coil energy consumption for a massless construction with temperature setback

Figure 72 represents the cooling coil energy consumption of EnergyPlus and WinAM for a massless construction with a temperature setback. The annual cooling consumption for EnergyPlus is 3,590 MMBtu and the annual cooling consumption for WinAM is 3,020 MMBtu.

The calibration for Simulation 2 recommended the following:

- Increasing peak occupancy from 200 ft^2/person to 130 ft^2/person
- Decreasing cooling coil setpoint from 55°F to 53.8°F
- Increasing peak occupancy from 130 ft^2/person to 94 ft^2/person
- Increasing peak occupancy from 94 ft^2/person to 85 ft^2/person
- Decreasing electric night load ratio from 0.4 to 0.38

After these changes were made, the WinAM total component error was at 15%, a value low enough to consider the model calibrated.

VI.III.III Simulation 3

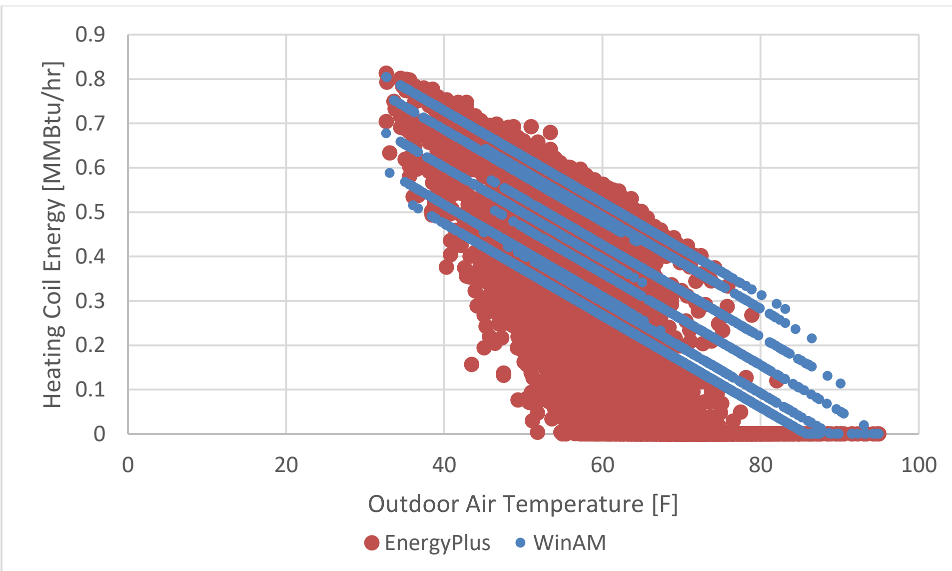

Figure 73: Hourly heating coil energy consumption for a light mass construction without temperature setback

Figure 73 represents the heating coil energy consumption of EnergyPlus and WinAM for a light mass construction without a temperature setback. The annual heating consumption for EnergyPlus is 3,060 MMBtu and the annual heating consumption for WinAM is 3,700 MMBtu.

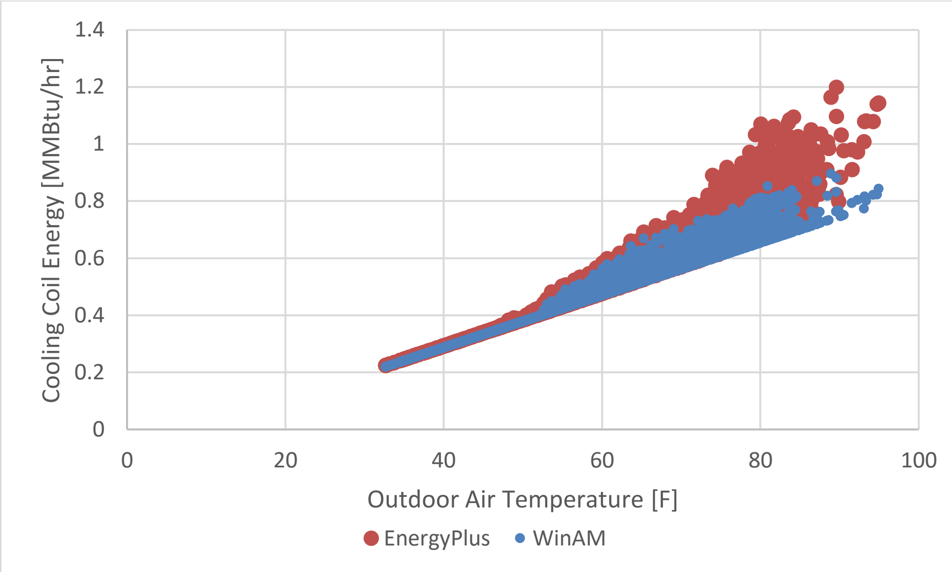

Figure 74: Hourly cooling coil energy consumption for a light mass construction without temperature setback

Figure 74 represents the cooling coil energy consumption of EnergyPlus and WinAM for a light mass construction without a temperature setback. The annual cooling consumption for EnergyPlus is 4,395 MMBtu and the annual cooling consumption for WinAM is 4,110 MMBtu.

The calibration for Simulation 3 recommended the following:

- Increasing peak occupancy from 200 ft^2/person to 97 ft^2/person
- Increasing peak occupancy from 97 ft^2/person to 71 ft^2/person
- Decreasing electric night load ratio from 0.4 to 0.38

After these changes were made, the WinAM total component error was at 11%, a value low enough to consider the model calibrated.

VI.III.IV Simulation 4

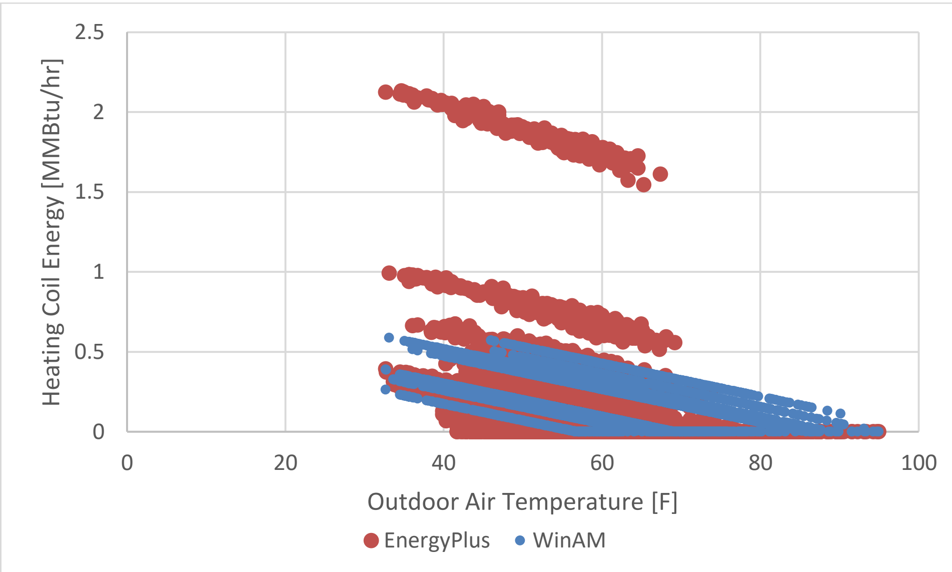

Figure 75: Hourly heating coil energy consumption for a light mass construction with temperature setback

Figure 75 represents the heating coil energy consumption of EnergyPlus and WinAM for a light mass construction with a temperature setback. The annual heating consumption for EnergyPlus is 1,690 MMBtu and the annual heating consumption for WinAM is 1,685 MMBtu.

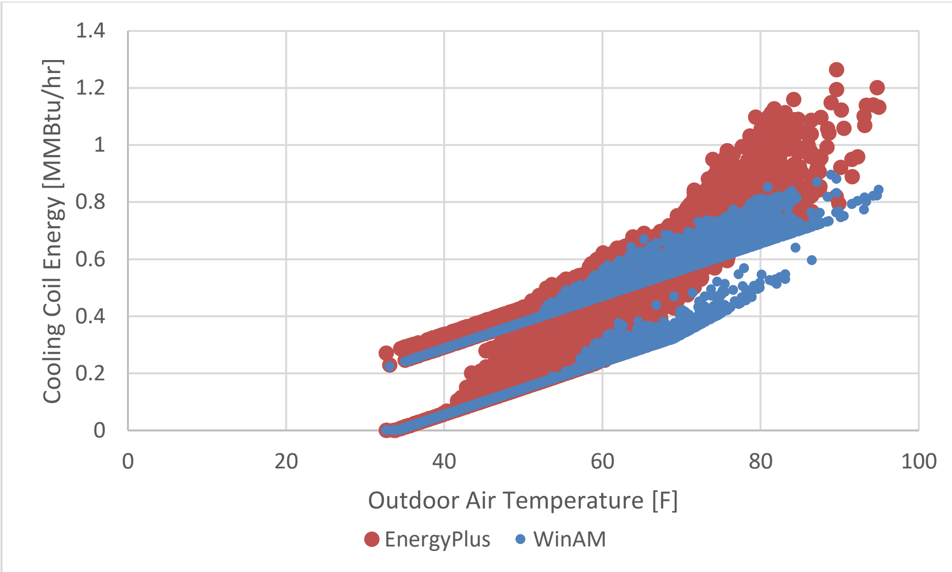

Figure 76: Hourly cooling coil energy consumption for a light mass construction with temperature setback

Figure 76 represents the cooling coil energy consumption of EnergyPlus and WinAM for a light mass construction with a temperature setback. The annual cooling consumption for EnergyPlus is 3,670 MMBtu and the annual cooling consumption for WinAM is 3,020 MMBtu.

The calibration for Simulation 4 recommended the following:

- Decreasing cooling coil setpoint from 55°F to 53.8°F
- Increasing peak occupancy from 200 ft^2/person to 97 ft^2/person
- Decreasing cooling coil setpoint from 53.8°F to 53.4°F

After these changes were made, the WinAM total component error was at 15%, a value low enough to consider the model calibrated.

VI.III.V Simulation 5

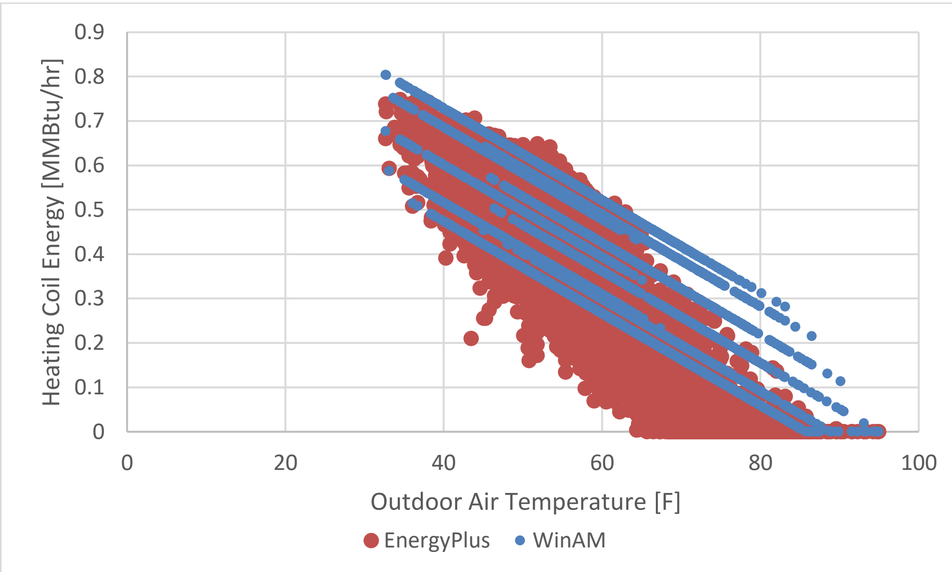

Figure 77: Hourly heating coil energy consumption for a heavy mass construction without temperature setback

Figure 77 represents the heating coil energy consumption of EnergyPlus and WinAM for a heavy mass construction without a temperature setback. The annual heating consumption for EnergyPlus is 2,930 MMBtu and the annual heating consumption for WinAM is 3,700 MMBtu.

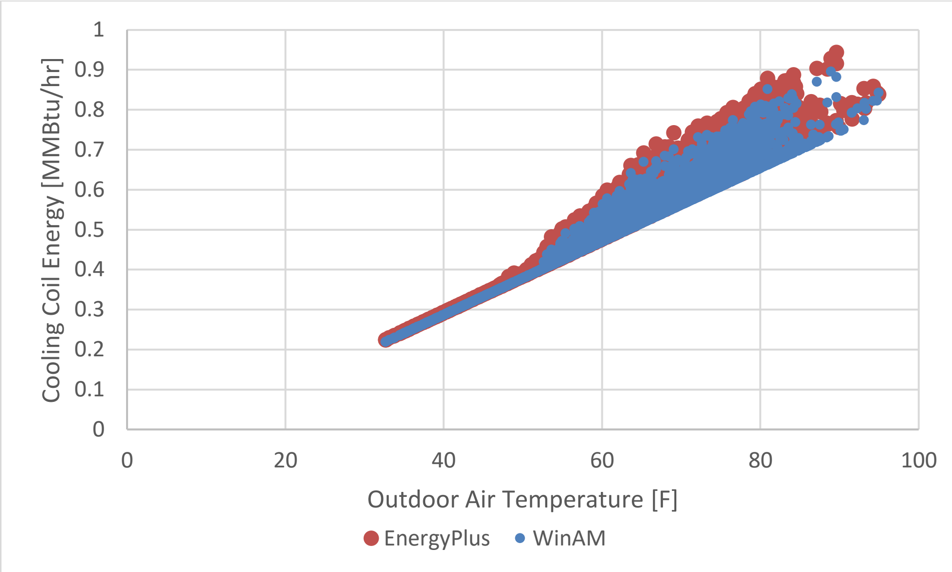

Figure 78: Hourly cooling coil energy consumption for a heavy mass construction without temperature setback

Figure 78 represents the cooling coil energy consumption of EnergyPlus and WinAM for a heavy mass construction without a temperature setback. The annual cooling consumption for EnergyPlus is 4,315 MMBtu and the annual cooling consumption for WinAM is 4,110 MMBtu.

The calibration for Simulation 5 recommended the following:

- Decreasing heating zone setpoint from 72^{o}F to 69.9^{o}F
- Decreasing cooling coil setpoint from 55^{o}F to 53.1^{o}F
- Increasing peak occupancy from 200 ft^2/person to 97 ft^2/person
- Increasing cooling coil setpoint from 53.1^{o}F to 53.5^{o}F

After these changes were made, the WinAM total component error was at 14%, a value low enough to consider the model calibrated.

VI.III.VI Simulation 6

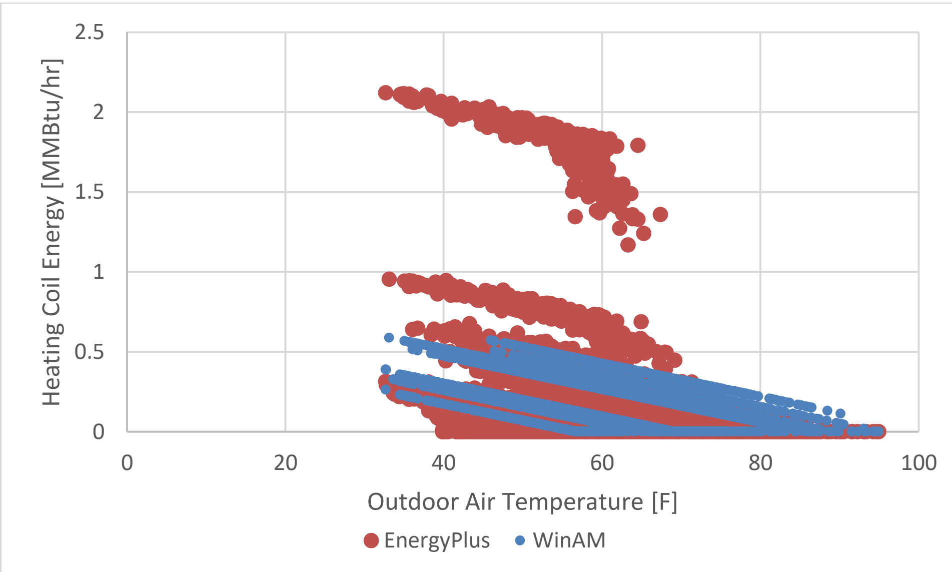

Figure 79: Hourly heating coil energy consumption for a heavy mass construction with temperature setback

Figure 79 represents the heating coil energy consumption of EnergyPlus and WinAM for a heavy mass construction with a temperature setback. The annual heating consumption for EnergyPlus is 1,745 MMBtu and the annual heating consumption for WinAM is 1,685 MMBtu.

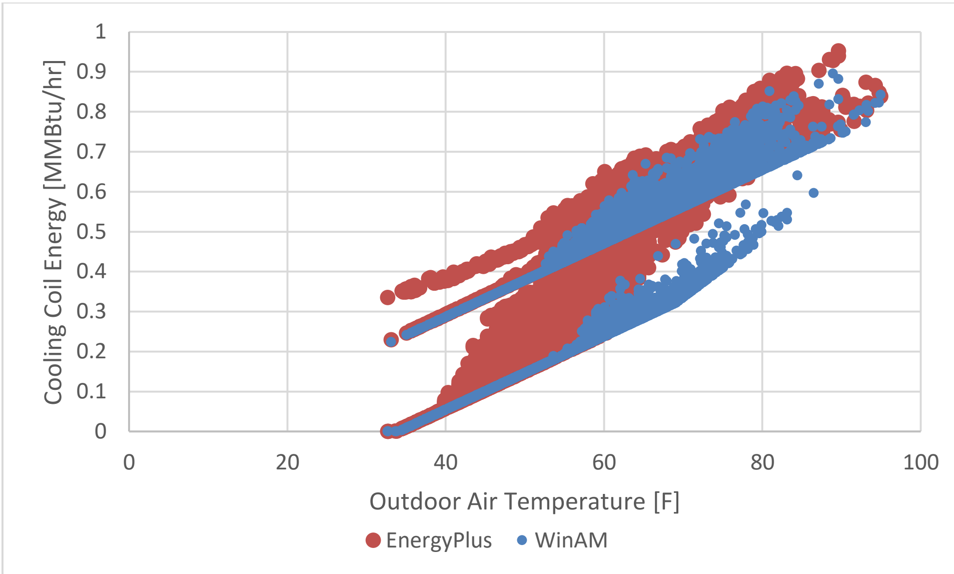

Figure 80: Hourly cooling coil energy consumption for a heavy mass construction with temperature setback

Figure 80 represents the cooling coil energy consumption of EnergyPlus and WinAM for a heavy mass construction with a temperature setback. The annual cooling consumption for EnergyPlus is 3,690 MMBtu and the annual cooling consumption for WinAM is 3,020 MMBtu.

The calibration for Simulation 6 recommended the following:

- Decreasing cooling coil setpoint from 55°F to 53.1°F
- Increasing peak occupancy from 200 ft^2/person to 97 ft^2/person
- Decreasing minimum occupied flow rate from 0.3 CFM/ft^2 to 0.29 CFM/ft^2
- Decreasing electric night load ratio from 0.4 to 0.39

After these changes were made, the WinAM total component error was at 14%, a value low enough to consider the model calibrated.

VI.III.VII Results Comparison and Analysis

As seen with College Station and Chicago, these results show high heating values and extra "tails" of cooling consumption for simulations with a setback. These points all occur at the hour when the system is changing from unoccupied to occupied or vice versa. The system is unable to meet the new temperature setpoint and in turn increases the flowrate for that hour. The increase in flowrate leads to a direct increase in coil energy.

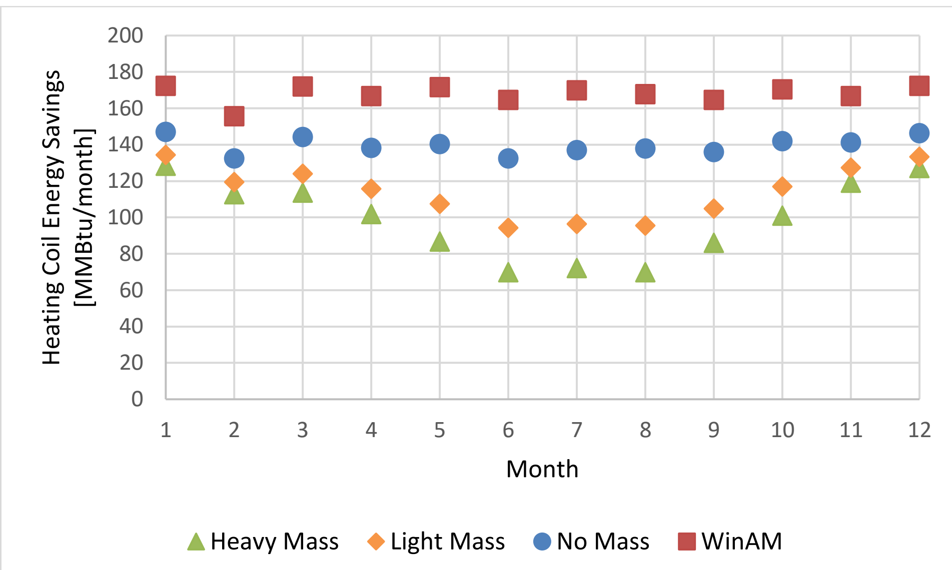

Figure 81: Monthly heating coil energy savings due to temperature setback

Figure 81 represents the monthly heating energy savings predicted when implementing a temperature setback. This figure follows a trend like the College Station climate. Overall, the heavier mass constructions predict less savings, with the summer months being the most extreme. The annual heating savings for each construction are the following:

- WinAM: 2,015 MMBtu
- No Mass: 1,675 MMBtu
- Light Mass: 1,370 MMBtu
- Heavy Mass: 1,190 MMBtu

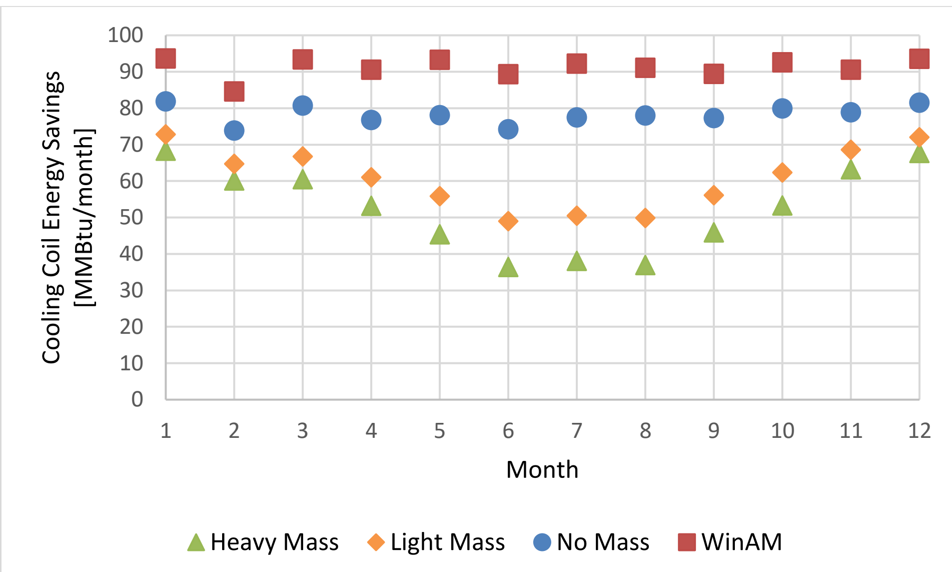

Figure 82: Monthly cooling coil energy savings due to temperature setback

Figure 82 represents the monthly cooling energy savings predicted when implementing a temperature setback. The savings predicted follows the same trend as the heating shown in Figure 81. The annual cooling savings for each construction are the following:

- WinAM: 1,090 MMBtu
- No Mass: 940 MMBtu
- Light Mass: 730 MMBtu
- Heavy Mass: 630 MMBtu

Like Chicago, every simulation recommends an increase in the peak occupancy by about double. Five out of six simulations also recommend lowering the cooling coil setpoint. These results support the assumption that WinAM is recommending these changes to change the heating and cooling load to behave more similarly to a simulation that accounts for thermal mass. It should be noted that there is a larger fraction difference between the No Mass EnergyPlus case and WinAM for this case than for College Station and Chicago.

VI.IV Climate Comparison

Although the three climates show varying consumption over the year, the simulations show similar trends in the computation of EnergyPlus. For example, all climates exhibited high heating at 7AM due to the change in temperature setpoint. All climates also showed decreased savings from a temperature setback during summer months when thermal mass is applied. Where the climates differ is in the lowest amount of savings due to temperature setback. The minimum amount of savings occurs around June and July for the three climates but vary in magnitude. In College Station, the minimum savings for heating and cooling are 28 MMBtu and 16 MMBtu, respectively. In Chicago, the minimum savings for heating and cooling are 53 MMBtu and 26 MMBtu, respectively. In San Jose, the minimum savings for heating and cooling are 72 MMBtu and 38 MMBtu, respectively. This means temperature setbacks are likely most effective in temperate climates, with 2.6 times more minimum heating savings of a hot climate like College Station. These results also reveal that a colder climate has almost double the minimum heating savings of a warm climate. A temperate climate likely caters best to a temperature setback because the walls of the buildings rarely hold the energy of extreme temperatures. For example, less heat stored in the walls allows the zone to more easily reach a new, cooler setpoint temperature after unoccupied hours.

CHAPTER VII

WINAM ADJUSTMENT METHOD

This section covers the method used to reduce the error in monthly energy consumption between WinAM and EnergyPlus models that include thermal mass. This method acts as a correction factor that is applied to WinAM to cause it to predict energy savings due to a temperature setback more closely to EnergyPlus.

The first step of this method was to calculate the difference in monthly energy savings due to setback between WinAM and the light and heavy mass EnergyPlus models seen in Figures 53, 54, 67, 68, 81 and 82. This was done for each location, and for heating and cooling. A linear regression was used to determine an equation that represents the correlation between outdoor air temperature and the difference in savings between EnergyPlus and WinAM for three different mass levels. The mass levels and their corresponding thermal capacitance are the following:

- Light mass: 50,000 Btu/hr-^{o}F (52,750 kJ/K)
- Heavy mass: 224,800 Btu/hr-^{o}F (237,200 kJ/K)
- Heaviest mass: 400,000 Btu/hr-^{o}F (421,750 kJ/K)

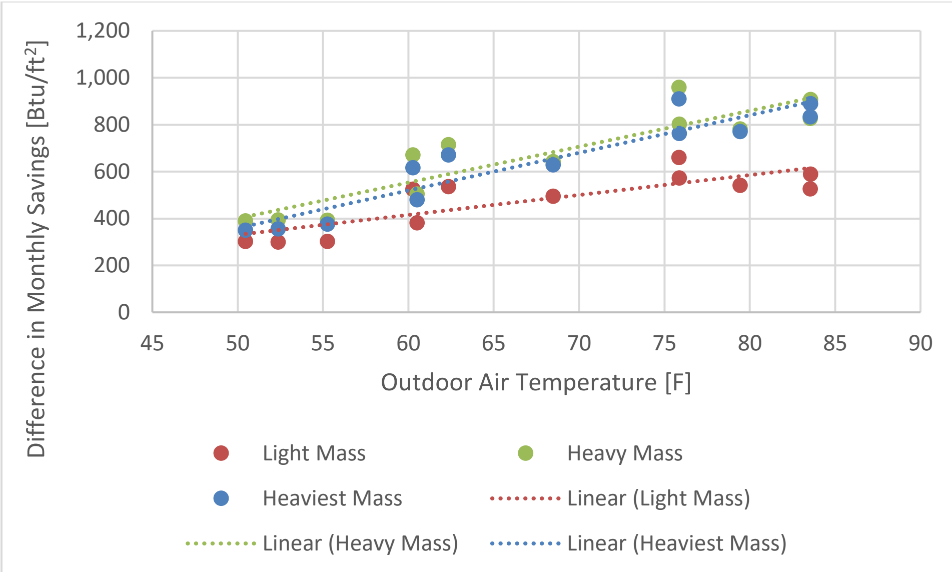

Figure 83: Linear regression of outdoor air temperature and difference in savings between WinAM and EnergyPlus for heating consumption in College Station

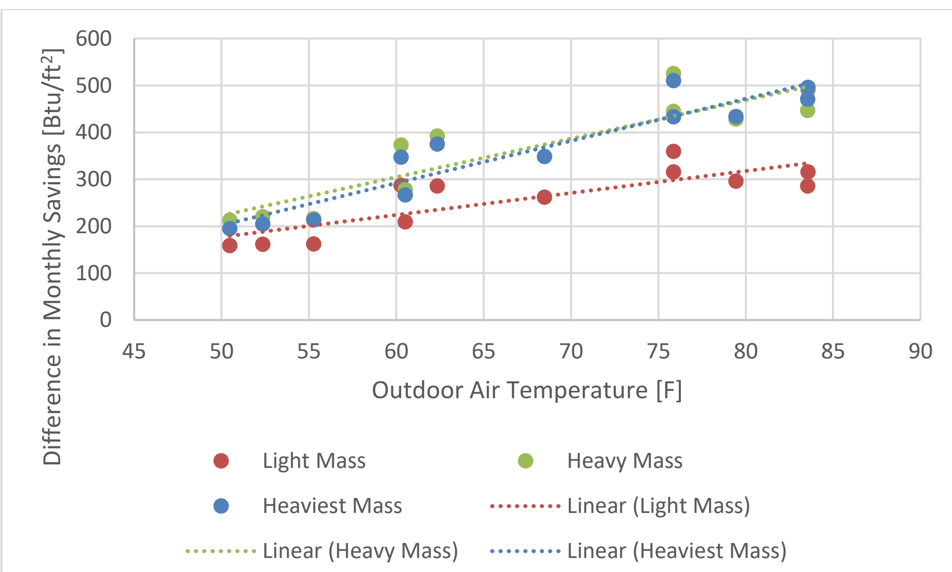

Figure 84: Linear regression of outdoor air temperature and difference in savings between WinAM and EnergyPlus for cooling consumption in College Station

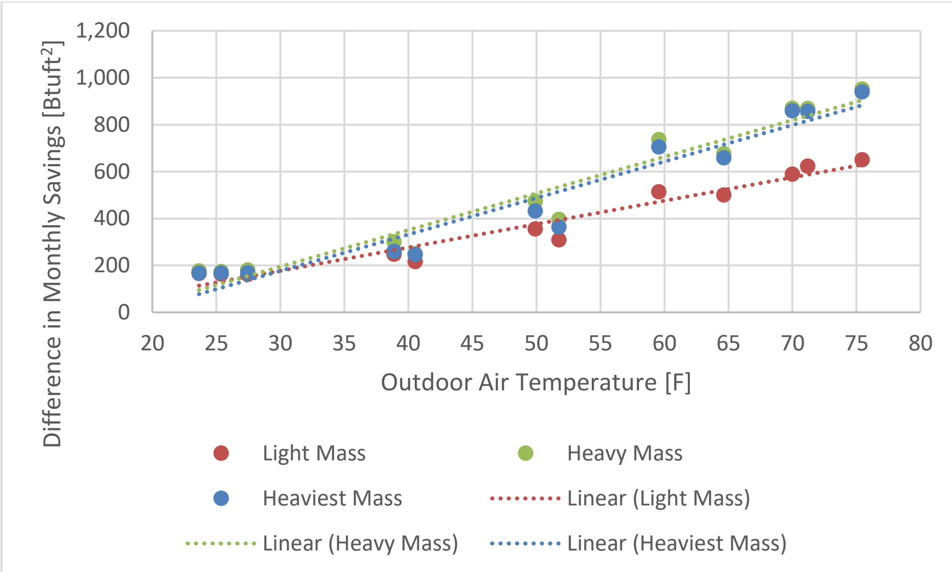

Figure 85: Linear regression of outdoor air temperature and difference in savings between WinAM and EnergyPlus for heating consumption in Chicago

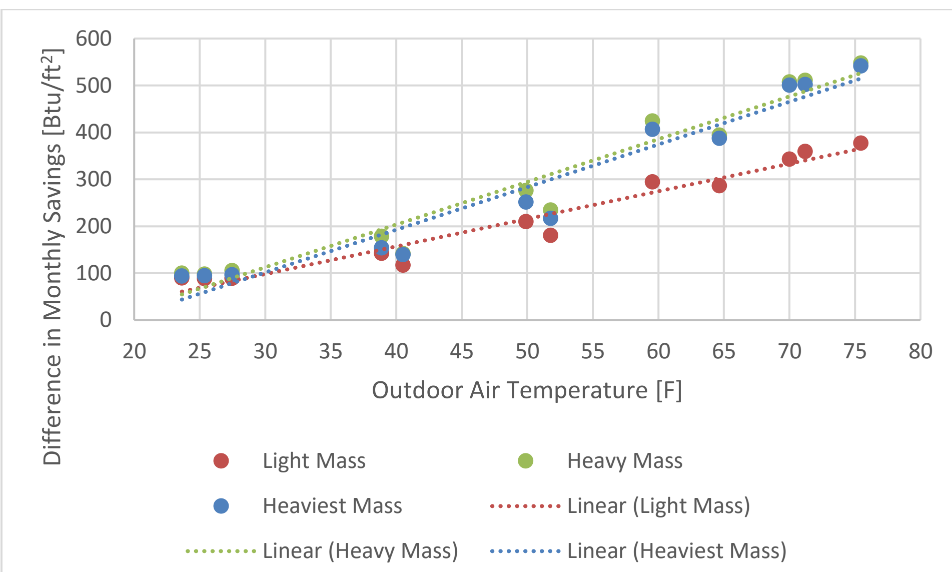

Figure 86: Linear regression of outdoor air temperature and difference in savings between WinAM and EnergyPlus for cooling consumption in Chicago

Figures 83-86 show the linear regression created by plotting outdoor air temperature versus the difference in savings between EnergyPlus and WinAM for three mass levels. A third mass level, heaviest mass, was created to increase the accuracy of the correction method.

Table 9: Linear regression equations relating outdoor air temperature to difference in savings for light mass construction

	Light Mass				
	Heating			Cooling	
	Slope [Btu/ft^2-°F]	Y-intercept [Btu/ft^2]		Slope [Btu/ft^2-°F]	Y-intercept [Btu/ft^2]
College Station	8.491	-93.985		4.6835	-57.03
Chicago	9.995	-121.2		5.879	-78.351
Average	9.243	-107.5925		5.28125	-67.6905

Table 10: Linear regression equations relating outdoor air temperature to difference in savings for heavy mass construction

	Heavy Mass				
	Heating			Cooling	
	Slope [Btu/ft^2-°F]	Y-intercept [Btu/ft^2]		Slope [Btu/ft^2-°F]	Y-intercept [Btu/ft^2]
College Station	15.308	-365.3		8.197	-187.2
Chicago	15.612	-273.5		9.102	-160.61
Average	15.46	-319.4		8.6495	-173.905

Table 11: Linear regression equations relating outdoor air temperature to difference in savings for heaviest mass construction

	Heaviest Mass				
	Heating			Cooling	
	Slope [Btu/ft^2-^{o}F]	Y-intercept [Btu/ft^2]		Slope [Btu/ft^2-^{o}F]	Y-intercept [Btu/ft^2]
College Station	16.04	-442.7		8.98	-246.8
Chicago	15.55	-289.8		9.092	-171.27
Average	15.795	-366.25		9.036	-209.035

Tables 9-11 show the slope and y-intercept produced from the linear regression. The slope and y-intercept values were averaged between College Station and Chicago because the values were similar. However, the San Jose slope and y-intercept from the linear regression were extremely different. It is assumed that the slope for San Jose varies from College Station and Chicago because of the small range in temperatures seen throughout the year. Because of this, the current WinAM correction method will only work for climates with a wide range of temperatures, similar to College Station and Chicago.

Next, the averaged slopes and y-intercepts for each mass level were then plotted against a special term, L, and a new linear regression was created. The special term is the thermal capacitance of the wall construction divided by the resistance of the wall construction. This term should not be confused with the time constant of the wall construction. This was done so that this method could be used with a wall construction of any thermal capacitance, i.e. thermal mass, and resistance.

$C = \frac{\rho \forall c_p}{1000}\ [kJ/K]$ **Equation 6**

Equation 6 is used to determine the thermal mass of a wall construction, where ρ represents density, $\forall$ is the volume of the wall layer, and c_p is the specific heat of the wall material layer. The thermal masses for each layer are summed to determine the thermal mass of the entire wall construction. With the thermal mass known, the special term, L, can be calculated by dividing by the wall resistance. Note that SI units should be used for calculating the special term L while the slope and y-intercept have English units. In future work, this should be updated to have consistent units.

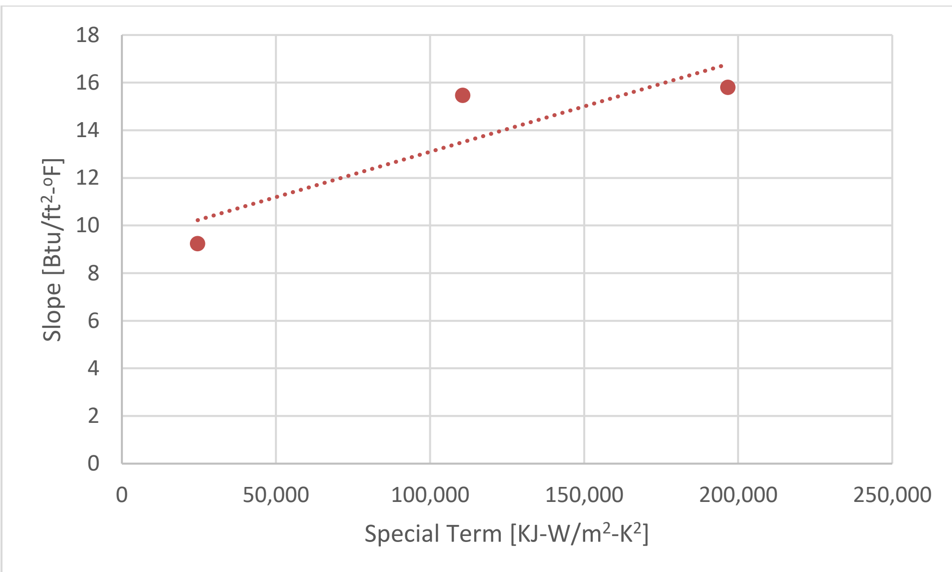

Figure 87: Linear regression of special term versus slope for heating

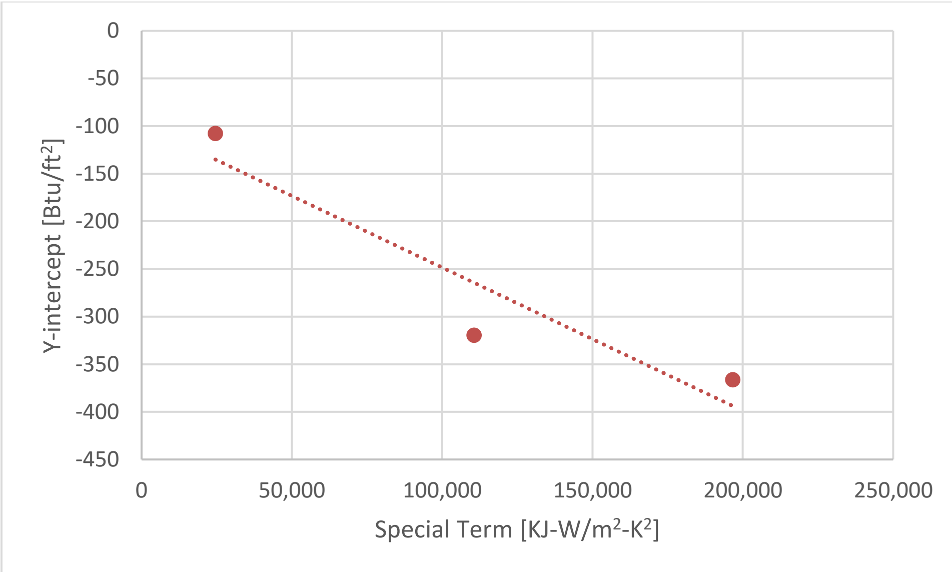

Figure 88: Linear regression of special term versus y-intercept for heating

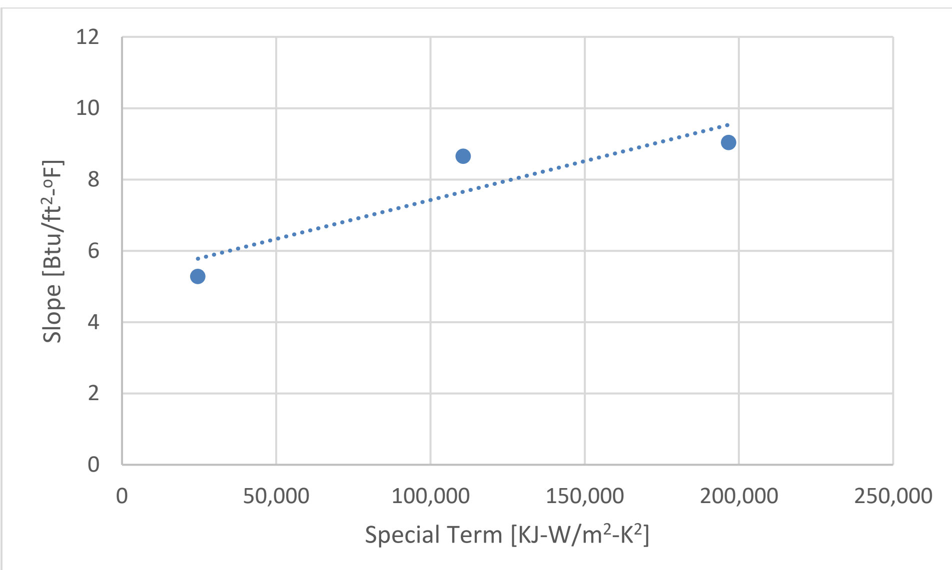

Figure 89: Linear regression of special term versus slope for cooling

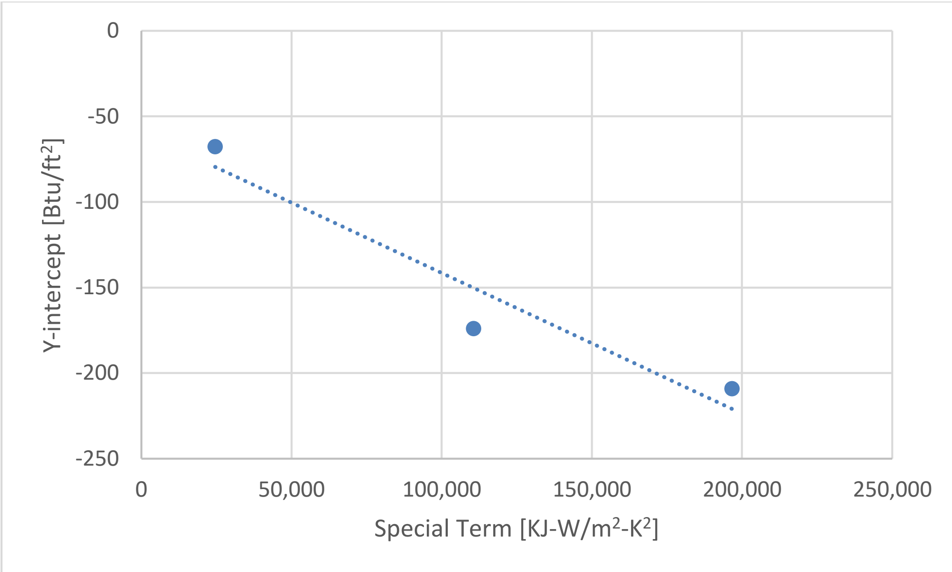

Figure 90: Linear regression of special term versus y-intercept for cooling

Figures 87-90 plot the slope and y-intercept versus the special term for heating and cooling. The linear regression equations created by these plots are the following:

$$\Delta heating = [(L * 4E^{-5} + 9.287)T_{OA}] + [(L * -0.0015) - 98.132] \;\; [Btu/ft^2 - mo]$$

Equation 7

$$\Delta cooling = [(L * 2E^{-5} + 5.242)T_{OA}] + [(L * -0.0008) - 59.344] \;\; [Btu/ft^2 - mo]$$

Equation 8

Equations 7 and 8 are used to correct the WinAM monthly consumption. These equations are used to determine a second equation that corrects the original WinAM consumption to a new WinAM consumption. It should be noted that Equations 7 and 8 only work for consumption in the units of Btu/ft^2, where Btu is the monthly consumption and ft^2 represents the building floor area. The first set of linear regression equations were created using these units so that any building size can be used.

$$New\ WinAM\ Heating\ Consumption = Old\ WinAM\ Heating\ Consumption - \Delta heating$$

Equation 9

$$New\ WinAM\ Cooling\ Consumption = Old\ WinAM\ Cooling\ Consumption - \Delta cooling$$

Equation 10

Equations 9 and 10 are the final equation used and determine the new, corrected WinAM monthly consumption per square foot of the conditioned space.

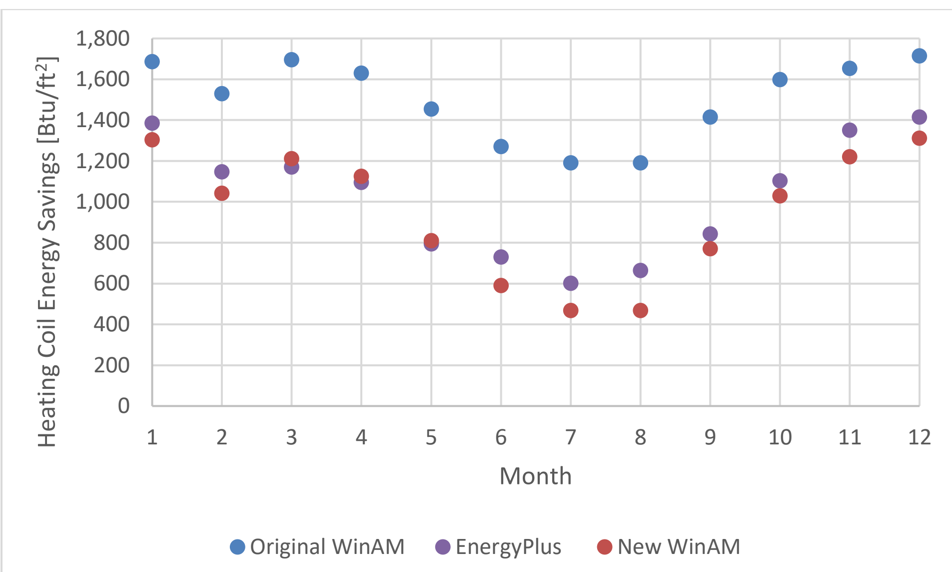

Figure 91: Monthly heating coil energy for a light mass construction in College Station

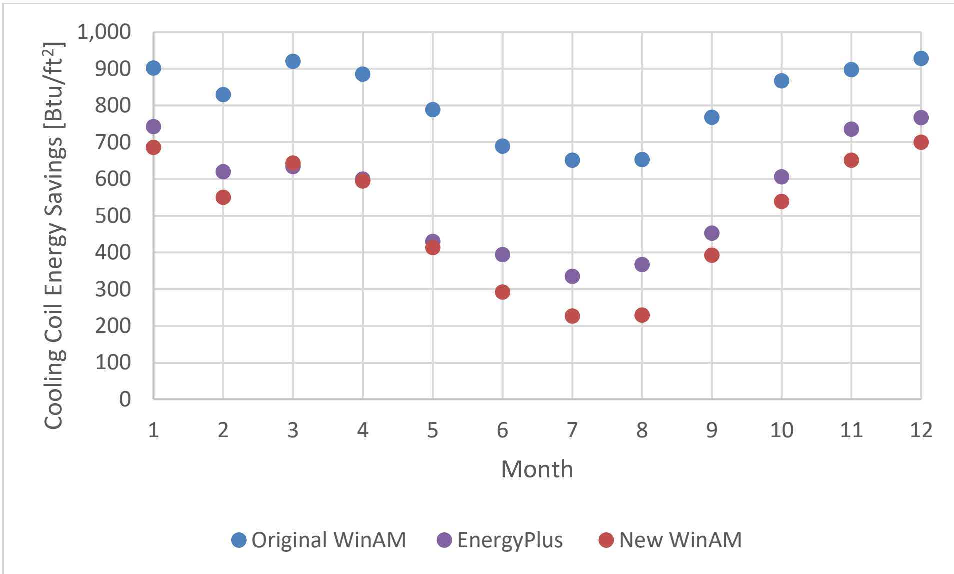

Figure 92: Monthly cooling coil energy for a light mass construction in College Station

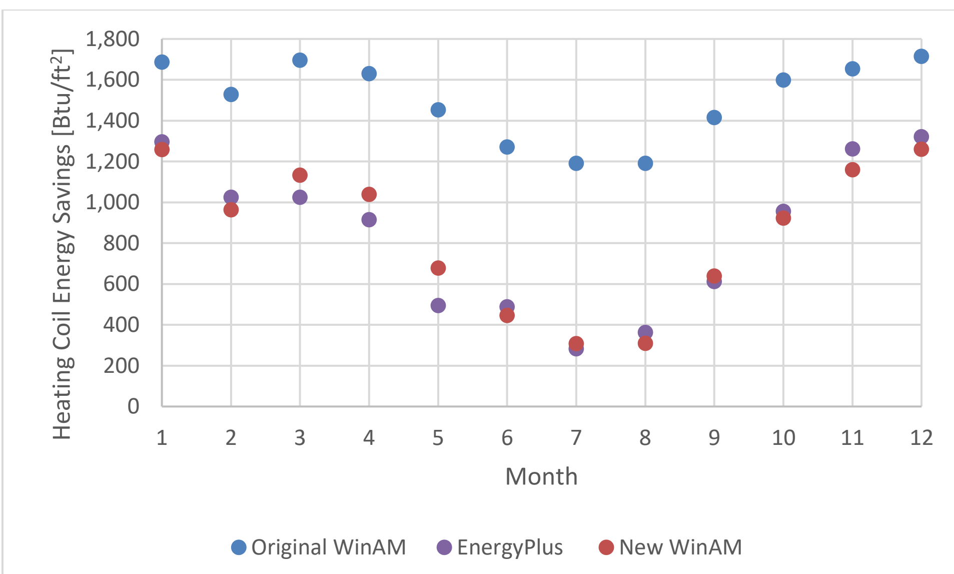

Figure 93: Monthly heating coil energy for a heavy mass construction in College Station

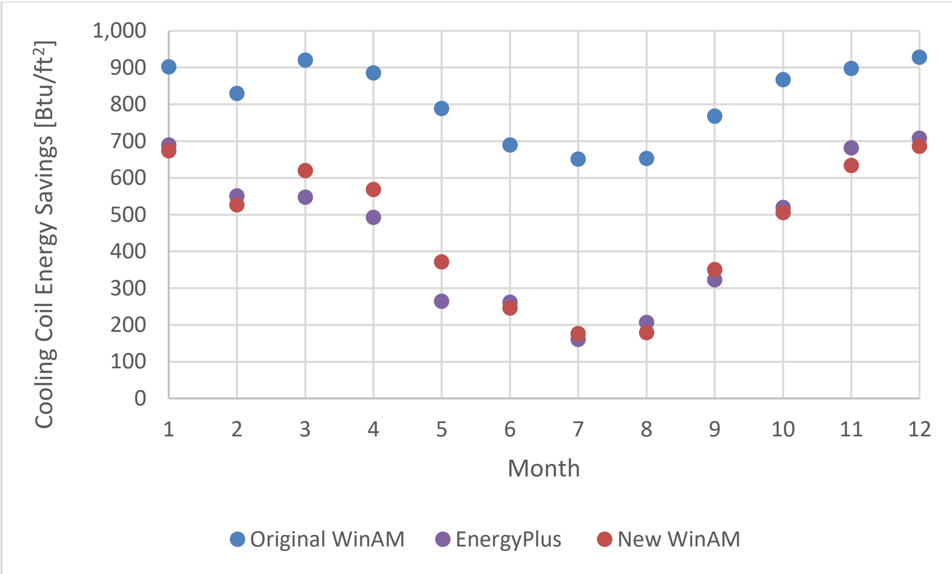

Figure 94: Monthly cooling coil energy for a heavy mass construction in College Station

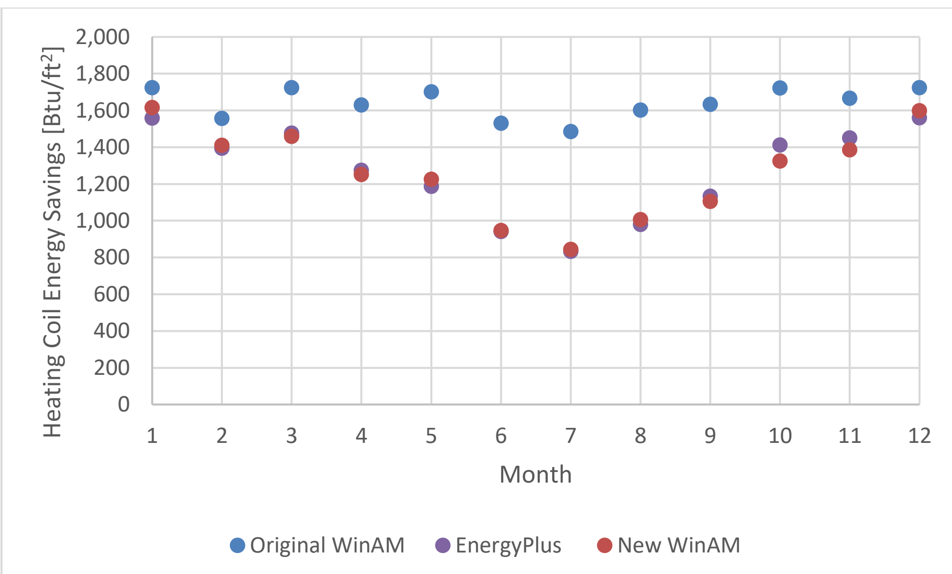

Figure 95: Monthly heating coil energy for a light mass construction in Chicago

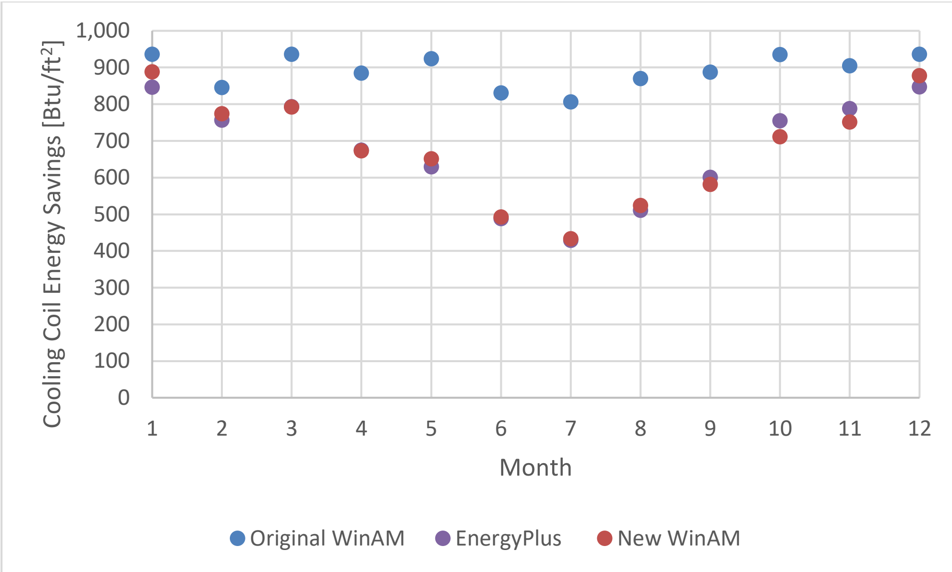

Figure 96: Monthly cooling coil energy for a light mass construction in Chicago

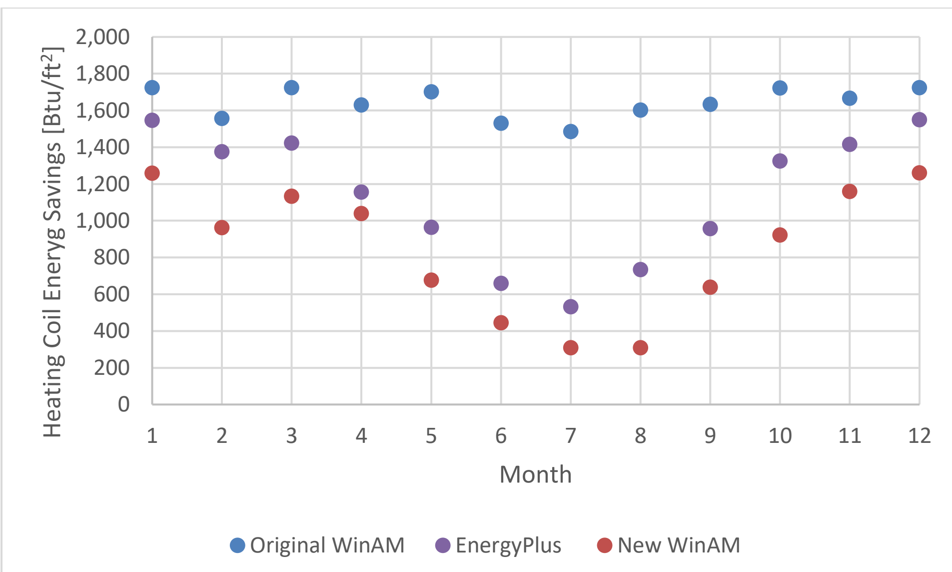

Figure 97: Monthly heating coil energy for a heavy mass construction in Chicago

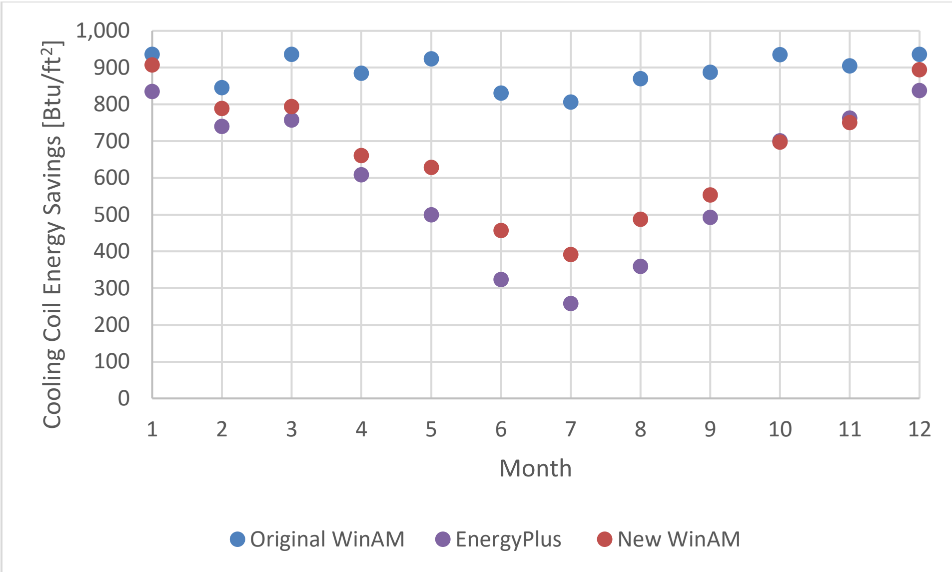

Figure 98: Monthly cooling coil energy for a heavy mass construction in Chicago

Figures 91-98 show the monthly energy savings for both heating and cooling coils, and heavy and light mass constructions in College Station and Chicago. The figures show predictions for monthly energy savings from EnergyPlus, original WinAM, and the new corrected WinAM. All figures show the new WinAM savings much closer to the EnergyPlus savings than the original savings predicted by WinAM.

Next, new models were created to test the method mentioned above. This section will go through how to use the correction method, along with results from implementing the method. The first test was changing the thermal mass of the wall while keeping the resistance the same as the heavy and light mass walls. For test 1, the special term, L, was calculated to be 153,607 KJ-W/m^2-K^2. Using Equations 7 and 8, test 1 Δheating=15.43T_{OA}-328.54 and Δcooling=8.31T_{OA}-182.23. The new WinAM savings prediction can now be calculated for heating and cooling as a function of outdoor air temperature. This process was repeated for tests 2-5 as well. Test 2 has an increased resistance value, increased from 12.18 hr-ft^2-ºF/Btu (2.145 m^2-K/W) to 17.73 hr-ft^2-ºF/Btu (3.122 m^2-K/W). Test 3 has the same wall construction as test 1 but a floor area of 50,000 ft^2 (4,645 m^2). Test 4 has a light mass construction with a minimum flow rate increased to 50%. Test 5 has a light mass construction with the minimum flow rate decreased to 25%. These parameters are summarized in Table 12.

Table 12: Changed parameters for each test

Test Number	Changed Parameter	Original Value	New Value
1	Special Term, L [KJ-W/m^2-K^2]	52,737	153,607
2	Wall Resistance [hr-ft^2-ºF/Btu]	12.18	17.73
3	Floor area [ft^2]	100,000	50,000
4	Minimum Flowrate [%]	30	50
5	Minimum Flowrate [%]	30	25

Table 13: Monthly savings due to temperature setback for EnergyPlus models Tests 1-3

	Test 1			Test 2			Test 3	
	Heating Savings [Btu/ft^2]	Cooling Savings [Btu/ft^2]		Heating Savings [Btu/ft^2]	Cooling Savings [Btu/ft^2]		Heating Savings [Btu/ft^2]	Cooling Savings [Btu/ft^2]
January	1309.59	692.91		1157.46	629.45		1192.12	653.92
February	1021.94	547.35		929.50	520.05		951.63	535.80
March	1035.10	549.78		965.82	537.02		984.12	548.17
April	921.43	488.50		880.04	494.32		891.87	499.42
May	491.47	249.23		620.74	344.26		585.20	317.76
June	472.69	239.64		597.45	331.06		567.96	305.30
July	258.13	130.29		469.95	251.90		398.05	210.13
August	329.72	166.60		505.60	275.22		453.57	241.97
September	612.95	312.51		690.00	387.81		672.45	366.59
October	946.99	505.47		914.42	518.28		923.52	519.03
November	1260.31	676.92		1120.46	624.05		1154.35	646.35
December	1330.37	710.35		1173.36	645.60		1206.50	670.07
Annual	**9990.71**	**5269.53**		**10024.80**	**5559.03**		**9981.34**	**5514.51**

Table 14: Monthly savings due to temperature setback for EnergyPlus models Tests 4-5

	Test 4			Test 5	
	Heating Savings [Btu/ft^2]	Cooling Savings [Btu/ft^2]		Heating Savings [Btu/ft^2]	Cooling Savings [Btu/ft^2]
January	2347.79	1650.47		1101.74	497.16
February	2066.43	1449.95		887.03	419.64
March	2223.41	1548.63		916.19	431.49
April	2123.42	1491.88		842.79	402.24
May	1997.25	1406.25		540.87	272.03
June	1925.61	1361.96		472.94	241.38
July	1826.64	1288.00		376.61	219.78
August	1881.87	1328.32		418.19	231.62
September	2021.22	1428.27		576.98	275.60
October	2214.99	1573.70		825.87	393.79
November	2273.61	1601.24		1100.94	518.58
December	2350.27	1648.55		1148.25	531.07
Annual	**25252.50**	**17777.22**		**9208.41**	**4434.38**

Tables 13 and 14 represent the EnergyPlus predicted monthly energy savings due to temperature setback in College Station. These are the values used to compare savings for the old and new WinAM models shown in the tables below.

Table 15: Monthly savings difference between WinAM Models and EnergyPlus for Test 1

	New WinAM [Btu/ft^2]			Original WinAM			Difference Reduction	
	Heating Difference [Btu/ft^2]	Cooling Difference [Btu/ft^2]		Heating Difference [Btu/ft^2]	Cooling Difference [Btu/ft^2]		Heating Reduction [%]	Cooling Reduction [%]
January	73.26	28.12		376.84	209.20		-80.56	-86.56
February	98.35	38.76		506.76	282.08		-80.59	-86.26
March	58.93	52.00		660.31	370.83		-91.08	-85.98
April	75.32	60.60		708.87	396.76		-89.37	-84.73
May	120.06	91.56		962.04	540.03		-87.52	-83.04
June	99.16	27.85		797.92	450.31		-87.57	-93.82
July	28.76	7.96		932.06	520.47		-96.91	-98.47
August	100.16	25.87		860.42	486.51		-88.36	-94.68
September	40.64	6.99		801.55	455.57		-94.93	-98.47
October	77.15	24.89		650.97	362.23		-88.15	-93.13
November	131.62	56.70		392.57	220.53		-66.47	-74.29
December	95.75	35.23		383.63	217.87		-75.04	-83.83

Table 16: Monthly savings difference between WinAM Models and EnergyPlus for Test 2

	New WinAM			Original WinAM			Difference Reduction	
	Heating Difference [Btu/ft^2]	Cooling Difference [Btu/ft^2]		Heating Difference [Btu/ft^2]	Cooling Difference [Btu/ft^2]		Heating Reduction [%]	Cooling Reduction [%]
January	11.29	46.44		414.15	273.61		-97.27	-83.03
February	54.50	14.96		506.86	316.07		-89.25	-95.27
March	66.22	89.95		624.31	389.28		-89.39	-76.89
April	67.63	84.59		653.93	399.26		-89.66	-78.81
May	66.13	89.78		835.20	503.87		-92.08	-82.18
June	85.92	2.69		731.46	443.06		-88.25	-99.39
July	63.45	30.46		809.83	501.24		-92.17	-93.92
August	105.37	9.09		767.69	479.75		-86.27	-98.10
September	42.25	23.44		727.00	437.63		-94.19	-94.64
October	47.46	16.81		621.77	376.59		-92.37	-95.54
November	65.01	13.90		425.40	276.40		-84.72	-94.97
December	26.74	41.72		424.38	282.85		-93.70	-85.25

Table 17: Monthly savings difference between WinAM Models and EnergyPlus for Test 3

	New WinAM			Original WinAM			Difference Reduction	
	Heating Difference [Btu/ft^2]	Cooling Difference [Btu/ft^2]		Heating Difference [Btu/ft^2]	Cooling Difference [Btu/ft^2]		Heating Reduction [%]	Cooling Reduction [%]
January	0.05	28.27		409.53	248.99		-99.99	-88.65
February	23.16	10.67		509.79	299.10		-95.46	-96.43
March	103.83	90.02		633.81	376.82		-83.62	-76.11
April	112.09	91.35		667.69	392.20		-83.21	-76.71
May	149.50	122.95		871.11	514.84		-82.84	-76.12
June	19.54	29.92		745.97	445.89		-97.38	-93.29
July	42.20	71.20		858.47	515.01		-95.08	-86.17
August	17.97	41.43		798.11	485.13		-97.75	-91.46
September	23.30	51.85		745.08	443.84		-96.87	-88.32
October	1.71	26.54		629.23	368.70		-99.73	-92.80
November	48.58	0.53		419.92	253.61		-88.43	-99.79
December	11.35	24.81		421.46	258.32		-97.31	-90.39

Table 18: Monthly savings difference between WinAM Models and EnergyPlus for Test 4

	New WinAM			Original WinAM			Difference Reduction	
	Heating Difference [Btu/ft^2]	Cooling Difference [Btu/ft^2]		Heating Difference [Btu/ft^2]	Cooling Difference [Btu/ft^2]		Heating Reduction [%]	Cooling Reduction [%]
January	137.24	60.11		246.00	155.77		-44.21	-61.41
February	210.08	97.59		276.33	181.48		-23.97	-46.23
March	113.77	20.09		370.16	257.46		-69.26	-92.20
April	119.12	34.89		386.22	255.77		-69.16	-86.36
May	65.68	11.72		578.39	387.35		-88.64	-96.97
June	126.90	33.43		553.85	364.66		-77.09	-90.83
July	64.37	42.36		658.80	466.43		-90.23	-90.92
August	145.35	2.49		577.66	426.46		-74.84	-99.42
September	165.61	63.18		478.60	312.54		-65.40	-79.79
October	195.62	100.94		372.68	228.28		-47.51	-55.78
November	196.04	99.34		236.51	146.74		-17.11	-32.30
December	159.21	70.12		243.52	157.70		-34.62	-55.53

Table 19: Monthly savings difference between WinAM Models and EnergyPlus for Test 5

	New WinAM			Original WinAM			Difference Reduction	
	Heating Difference [Btu/ft^2]	Cooling Difference [Btu/ft^2]		Heating Difference [Btu/ft^2]	Cooling Difference [Btu/ft^2]		Heating Reduction [%]	Cooling Reduction [%]
January	66.13	70.92		317.11	144.96		-79.15	-51.08
February	83.11	86.46		403.31	192.61		-79.39	-55.11
March	49.39	17.69		533.32	259.86		-90.74	-93.19
April	35.02	33.27		540.36	257.39		-93.52	-87.07
May	72.80	117.21		571.27	258.41		-87.26	-54.64
June	240.78	204.06		439.96	194.03		-45.27	5.17
July	273.12	248.70		450.05	175.37		-39.31	41.81
August	309.08	257.75		413.93	166.22		-25.33	55.06
September	154.01	142.33		490.20	233.39		-68.58	-39.02
October	90.80	101.37		477.49	227.85		-80.98	-55.51
November	119.14	93.22		313.42	152.86		-61.99	-39.01
December	83.36	73.18		319.37	154.63		-73.90	-52.67

Tables 15-19 show the raw difference between monthly savings of EnergyPlus and both the original and corrected WinAM models in College Station. A lower value in this table indicates a closer match to the EnergyPlus savings prediction. The tables also show the percent reduction of this difference between the original WinAM and the new WinAM in the columns on the right side of the tables. For example, for July cooling in College Station, the difference in savings predicted between WinAM and EnergyPlus decreases by 98.5%. This reduction reveals an increased accuracy for the corrected WinAM predicted savings.

This method proves to greatly improve the WinAM savings prediction due to temperature setback when thermal mass is applied. Tables 15-18 show the WinAM correction method reducing the difference between monthly savings of EnergyPlus up to 99%. However, Table 19 shows the method not working in summer months. Table 19 represents the savings for Test 5, a model with the minimum flow reduced to 25%. When the minimum flow is reduced below 30%, the trend between outdoor air temperature and the difference in savings starts to change. For the 30% minimum flow, the heating savings difference between WinAM and EnergyPlus increases as temperature increases; for the 5% and 25% minimum flow, the heating savings difference decreases as temperature increases. Because of this opposing trend seen for minimum flow below 30%, the WinAM correction does not apply to models with low minimum flow. However, most buildings in practice operate at 30% minimum flow or above, so the WinAM correction method is still useful for these buildings. It should be noted that this method has not been tested for heavy glazed constructions, multi-story buildings, or multi-zone constructions. This method also only applies to VAV systems.

CHAPTER VIII

CONCLUSIONS AND FUTURE WORK

This research revealed the complex nature of EnergyPlus and its input method. Through trial and error, a simple baseline was created that can be used as a starting point for future work. This baseline can be trusted because of the validation process discussed in Chapter III.

Results from Chapter IV indicate that thermal mass effects as much as tripled WinAM energy consumption discrepancies compared to EnergyPlus for the cases examined. This section determined the error between WinAM and EnergyPlus results was below 5% until thermal mass was introduced into the simulation. At this point, the error between the two programs increased to roughly 15%. Work done in Chapter IV also revealed that matching weather data is required when calibrating WinAM to the EnergyPlus model.

Results from Chapter VI show that WinAM does not accurately predict the energy savings of a temperature setback when thermal mass is included in the building. The figures in this section show increased spread in EnergyPlus predicted consumption compared to WinAM. WinAM currently overpredicts the total savings of a temperature setback by a factor of 1.45-1.81 on an annual basis for the cases examined. However, it is possible to adjust the WinAM predicted savings in a simple manner to more accurately represent a real building. The WinAM adjustment method discussed in Chapter VII can easily be implemented into the code of WinAM and would only add one new input page, which would be wall construction details. Results show implementing the adjustment method would lead to a reduction in the raw savings difference between EnergyPlus up to 99%. The new WinAM monthly savings prediction is more realistic and only overpredicts annual savings of a temperature setback by a factor of 1.00-1.09, eliminating the misleading nature of the current WinAM model prediction.

The baseline model created in this research works as an excellent starting point for many different uses. The baseline can be made more intricate to be used for future work without worrying about many of the bugs discovered while making it. Future work includes developing a more robust WinAM adjustment method and repeating the thermal mass effect simulations with a real building. Chapter VI of this report can be improved by repeating a similar process but with a real building in the similar climates discussed. Modeling a real building allows for verification of both WinAM and EnergyPlus outputs since they can be compared to the metered data of the building being modeled. Future work also includes observing solar effects since they are not considered in WinAM.

The WinAM correction method can be improved my increasing the number of models used to create the two sets of linear regressions. The first linear regression can be improved by creating models in different climates. Currently, the equations are averaged between two climates, but the accuracy of these equations would increase with added climates. The second linear regression can be improved by creating more models with varying thermal mass and wall resistance. There are currently three mass models used to create the linear regression. Adding more models could lead to a new equation type that increases the accuracy of the regression. This correction method can also be improved by investigating other parameters, such as window area, minimum flowrate, and outdoor air percentage. Future work also includes integrating minimum flow rate into the correction method. Currently, the method works best for buildings operating at 30% minimum flow and works well with minimum flow above 30%. However, the method fails when the minimum flow drops below 30%. Minimum flow could be integrated into the correction method by creating several models of varying minimum flow and thermal mass levels to see how the two are related.

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